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Risø-R-Report

Dansk Gasteknisk Center a/s

Risø DTU
National Laboratory
for Sustainable Energy

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Abstract:

Danish:
Det er i dette projekt forsøgt at kortlægge potentialet for fremstilling af SNG via forgasning af biomasse. Der er i denne forbindelse blevet udviklet en model til at simulere forskellige scenarier for biomasse i Danmark. Det kan konkluderes, at SNG kan substituere en væsentlig mængde naturgas, produktionen bør dog energieffektiveres.

English:
In this project the potential for SNG based on biomass gasification has been sought elucidated. As part of the project a model for simulation of biomass in Denmark has been developed. The conclusion is that SNG can substitute a significant amount of natural gas, but the energy efficiency should be improved.

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Foreword and introduction

The following report is the product of a Forsk-EL project that seeks to evaluate the technical and biological potential for integration of synthetic natural gas made from gasification of biomass (Bio-SNG) into the Danish natural gas infrastructure. It is no simple task to evaluate the possibilities and potential impact of such a significant alteration of an existing sector, and therefore it is only the more important to get the process started. This report is the first step in that process.

The project is contracted by Energinet.dk and the work is conducted in a joint effort between DGC (Dansk Gasteknisk Center) and the Biomass Gasification group under Biosystems Division at Risø DTU. The work is theoretical, and based on literature studies, workgroup discussions and simple calculations. The focus of the work is on the technical and biological potentials of a near future integration of bio-SNG in the Danish energy sector.

The report has been structured so that it initially gives a short introduction to the Danish gas infrastructure. Following this, a review of the present status of SNG production via biomass gasification, with two examples of coal gasification as well, is given. In chapter 4 foreign experiences with SNG is summarized and compared to Danish conditions.

In chapter 5 the biomass potential in Denmark is thoroughly elucidated. Three scenarios for 2020 are drawn up and compared. Finally, the potential for SNG in Denmark is evaluated based on the previous chapters, and recommendations for future work are given.

The project was funded by Energinet.dk's research programme ForskNG, and the workgroup is very thankful to ForskNG for this possibility.

Summary

Synthetic Natural Gas potential and efficiency

Denmark has had the fortune of being self-sufficient in natural gas. With the expected depletion of the fossil fuel resources, although not for several years, it is necessary to find an alternative to natural gas. Furthermore, environmental issues are becoming more and more important, one example is the Kyoto agreement, but also European and national politics aim to meet requirements for a sustainable energy production, where fossil resources are to be replaced by renewables.

Over the last 25 years the Danish gas infrastructure has been developed and gas can be delivered to most parts of the country. It would, therefore, be thoughtless not to utilise this commodity for future distribution of energy. One possibility is to inject SNG (Synthetic Natural Gas) into the natural gas grid, either biogas produced from anaerobic digestion or SNG from thermal gasification of biomass. In order for the gas to be injected it need to fulfil the requirements stated in the Danish national Gas Regulations (Gasreglementet). This project focuses on thermal gasification and has evaluated both the available technologies as well as the biomass potential.

SNG from thermal gasification - Technologies

Thermal gasification can be divided into two main groups; direct and indirect gasification. In direct gasification some of the biomass is combusted in order to reach the gasification temperature and an oxygen-rich gas is used, e.g. air or pure oxygen. In indirect gasification the heat is generated outside the gasifier. Originally, the gasification process was developed for coal gasification and examples of SNG production from coal are included. The existing biomass gasification technologies favour woody feedstock.

In the gasification process the biomass is converted into a product gas, with main components CO, CO_2, CH_4, H_2 and water. In order for the gas to be classified as SNG a methanation step is necessary to increase heating value and Wobbe index. For SNG production it is an advantage if the product gas is free of nitrogen.

There are some commercially operating biomass gasification plants, but none were initially designed for SNG production. A short summary of three of the commercially running gasifiers is given, namely the MILENA gasifier developed by ECN, the FICFB (Fast Internally Circulating Fluid Bed) gasifier from the Pau-Scherrer Institute (used in Güssing) and the SilvaGas gasifier.

Two methanation technologies are presented, the HaldorTopsoe TREMP™ process and the Linde and LurgiRectosol® process.

A comparison of selected bio-SNG plants showed that the best SNG efficiency is reached with a fluidised bed and an indirect gasifier. The SNG efficiency is defined as the energy in the SNG product divided by the total energy input including biomass, drying and oxygen. Comparing the two methanation processes showed very little difference in the results and also the gas clean up systems showed a non-significant difference.

Bio-SNG experiences

Bio-SNG has attracted interest in other countries as well. To highlight this, examples from the Netherlands, Sweden, Chile and Canada are given.

Denmark will not be the first European country to distribute bio-SNG. In the Netherlands natural gas contributes to almost half of the primary energy consumption and more than 90 % of the heat production. The Dutch natural gas grid is very well-established and they have started adding bio-SNG. Their ambition is to replace 50 % of the natural gas with bio-SNG. In order to meet this goal it is necessary to find alternatives to biogas and landfill gas, and in the Netherlands focus has been on gasification, with the development of the MILENA gasifier. In august 2010 the first upgraded biogas was added to the transmission network, hereby distributing biogas to a larger area.

In Sweden there is already an elaborate use of biogas, though it is mainly used for transportation or in closed networks where natural gas is absent. Two recent studies have looked at biomass gasification for SNG production combined with district heating; the studies take place in Linköping and Göteborg.

In Linköping three technologies are proposed for supplying district heat to a larger area; the Güssing process connected to a gas engine for CHP production with woodchips as feedstock. The Värnamo process integrated in a combined cycle. And, finally, an SNG production plant where district heat is produced as a by-product.

In Göteborg a quite elaborate project where heat, power and transportation fuels are coproduced from biomass gasification has been investigated. The GOBIGAS project has received founding from the Swedish Government and will use the Güssing technology for the first plant, which is to produce 20 MW SNG. Sweden has the advantage of vast wood resources, which makes it possible to use existing technologies.

In Chile the consumption of natural gas has been rapidly growing, and Chile imports the majority from Argentina. In order to reduce the dependence of other countries a study of the possibilities for bio-SNG production was made. The biomass potential in Chile is estimated to be around 870 PJ, with the majority in wood and forest residues. Chile has the disadvantage that the existing natural gas grids only cover small areas, and due to the geography of Chile it is not possible to connect the grids. It will, therefore, be necessary to have a more decentralised collection of biomass than what will be the case in Denmark.

In Canada the potential for bio-SNG has also been studied. Here the background is based on two different scenarios. The study shows that bio-SNG can, dependent on the scenario, substitute between 16 and 63 % of the consumption of natural gas. Canada also has the advantage of vast reserves of wood.

Estimation of the biomass potential in Denmark

In order to assess biomass potential in Denmark a model for calculating the biomass potential was developed. The model uses 2007 as the reference year and there are three overall areas that can be used to mimic certain conditions, they are: land area usage, crop and production characteristics, and biogas production. The land area usage contains the available area of land divided into farm crop soil, fallow land and forests. When this is set the choice of crops is the next variable. Based on a database over the most common crops in Denmark the crop production energy input and LHV of the biomass can be calculated. Finally the quantity of animals is to be chosen. The biomass potential calculator was compared to an equivalent calculator and found to give results that do not vary more than 2 %.

To estimate the biomass potential in 2020 three scenarios were evaluated.

The included scenarios are:

- A political scenario built on the ambition to maintain business-as-usual in agriculture, but still meet the 2020 goal. The main internal changes come from utilization of farm soil for energy crop production and increased utilization of straw, manure and other production residues for energy purposes.
- A climate change scenario based on predictions about climate change impact on farming conditions in Denmark. Variations in crop yields, changes in the selection of suitable species for more robust business and production setups, and an increase in the use of pesticides and herbicides are main influential factors in this scenario.
- A scenario thriving for a more environmentally concerned and sustainable agricultural management. In this scenario some of the harmful long term effects of modern agricultural management are mitigated with structural changes in land use, increased biodiversity and decreased animal production. Climate change effects are not included in this scenario.

The scenarios were compared on the amount of biomass (PJ) available divided into wet and dry biomass, the energy input and the energy return (LHV) on energy investment ratio. In order to meet the EU goal of 30 % sustainable energy in 2020 it is estimated that 145 PJ is to come from biomass. None of the scenarios reached this goal, however the last scenario is only 3 PJ short of reaching the 145 PJ. It is important to notice that in this estimation municipal waste was not included as a renewable energy feedstock.

The Danish bio-SNG potential

The bio-SNG potential was estimated based on the known technologies and the estimated biomass potential for 2020. It was assumed that woody and herbaceous biomass can be converted trough gasification; in addition the anaerobic digestion of wet biomass was also included. It was found that under the given conditions a potential around 100 PJ of bio-SNG will be available in 2020, including only Danish feedstock. If the consumption of natural gas remains constant this will amount to around 50 % of the gas consumption in Denmark. The amount of bio-SNG could be increased further by developing the gasification technologies so that more feedstocks could be applicable for gasification.

The given potential for bio-SNG presupposes that all available biomass is utilised in gasification. This is not likely to be the case. Denmark does not possess vast amounts of woody feedstock, which at present is the most energy efficient feedstock for gasification.

Future recommendations

This report estimates the bio-SNG potential in Denmark. Some assumptions were made and this leaves room for improvement.

One of the areas that could be improved is the gasification technology. It would be a great improvement if there were to be developed a technology with the simple purpose of producing SNG from a variety of feedstocks. In order to accomplish this, a thorough analysis of thermodynamics and the chemistry of the overall process is necessary. Furthermore, the model developed in this project could also be refined.

In summary, the work shows that there is a potential for bio-SNG in Denmark. Though with the present technologies it might not be the most optimal way of utilising the biomass resources, but there is still the advantage that the energy can be stored and easily distributed to the majority of the country.

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1 Natural gas in the Danish energy sector

In 1979 it was decided by the Danish Government to introduce natural gas in the Danish energy sector. The introduction and expansion of the infrastructure was rapid, and today most of Denmark's cities, towns and villages are connected to the natural gas grid, receiving natural gas from the Danish gas fields in the North Sea (DGC).

Denmark has been self-sufficient with natural gas in several years, with a production/consumption peak around 2005. In that year production was 393 PJ and consumption only 188 PJ, resulting in a > 200% self-sufficiency level (Energistyrelsen, 2010). Production has been slowly declining since 2005, and consumption has been declining since 2006. Based on statistical data, consumption trends and expectations on technological advancement, Denmark is often estimated to be self-sufficient with natural gas for another 20 years (DGC).

Natural gas is not the only energy source to experience a decline in consumption in recent years. Actually, all fossil energy carriers used in the Danish energy sector (coal, coke, oil and natural gas) have a diminished representation in the Danish energy consumption compared to earlier. This is not only due to the slow reduction of the overall energy consumption in Denmark that has been going on since 2006, but is also due to the fact that the share of sustainable energy and energy from waste is growing steadily (Energistyrelsen, 2010).

There are many reasons – both political and environmental, why it is desirable to have a large share of sustainable energy. Reduced greenhouse gas emissions, increased energy security and improved economy are some of them. Human influence on climate changes is being debated heavily all over the globe, and frontrunner governments are committing themselves to reductions in greenhouse gas emissions and increases in the production of sustainable energy. In 2007 the Danish Government decided to work towards a doubling of the share of sustainable energy in the Danish energy sector before 2025 with an additional ultimate goal of liberating the sector completely from the dependence on fossil fuels (Energiministeriet, 2007).

This report examines the potential of producing Synthetic Natural Gas from biomass (Bio-SNG), including the existing natural gas infrastructure in the utilization. If this manoeuvre is beneficial under Danish conditions, it could potentially be a new method to further reduce the consumption of fossil fuels and increase the share of sustainable energy in the Danish energy sector.

2 The basics of bio-SNG production and Danish gas infrastructure

2.1 Main production steps and reactions

Bio-SNG is usually made by upgrading product gas from the thermal gasification of biomass, whereas classic SNG is usually made by upgrading product gas from the thermal gasification of coal or other fossil sources.

Various technological approaches to this process are assessed later on in the report together with a couple of alternative production systems – Bio-SNG from biogas and hydrothermal gasification.

The general Bio-SNG/SNG production pathway is usually a four-step process as shown in Figure 2-1:

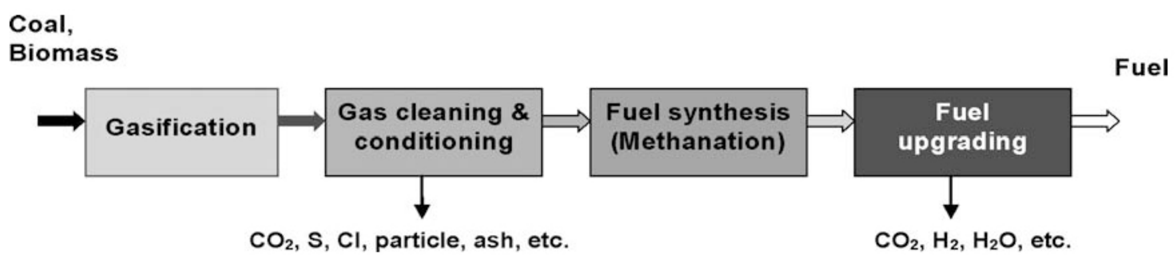

Figure 2-1: General production pathway for BIO-SNG/SNG (Kopyscinski, et al., 2010)

The product gas from the first step in the SNG production chain consists largely of CO_2, CO, CH_4, H_2 and H_2O with some impurities (like sulfur and chlorine species) and a large amount of N_2 if atmospheric air was used in the gasification. The composition of a specific producer gas depends heavily on carbon-source, gasifier design and process parameters (Kopyscinski, et al., 2010).

To make the use of Bio-SNG feasible, it is important to be able to utilize the existing natural gas infrastructure. There are many requirements that a gas have to meet to be allowed into the Danish natural gas grid and because the main amount is delivered from domestic sources in the North Sea, restrictions in the Danish gas grid are stricter than in many other countries. A consequence of the high restriction level in Danish gas infrastructure is increased costs and requirements for effective gas cleaning and conditioning operations and for the fuel synthesis itself.

Gas cleaning removes impurities and prepares the gas for fuel synthesis. It is important to have a well defined gas for synthesis reactions, as these normally run over catalysts that may be damaged or destroyed by unwanted components in the gas. In addition to this, there are requirements from the gas grid gatekeepers and all in all the native producer gas has to be largely altered to yield usable SNG or Bio-SNG.

The conditioning of the producer gas normally involves steam reforming and water-gas shift reaction, which are described below (Kopyscinski, et al., 2010):

$$C_XH_y + x\,H_2O \leftrightarrow x\,CO + \left(x + \frac{y}{2}\right) H_2 \Delta H_R^0 > 0 \quad (reaction\ 1)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \Delta H_R^0 = -41\,\frac{kJ}{mol} \qquad (reaction\ 2)$$

The next step of the SNG production involves fuel synthesis. This is called methanation in the case of SNG-production and it is a reaction that takes place over catalysts, converting hydrogen and carbon oxides to methane (Knoef, 2005).The overall methanation process is described below, through a series of more or less involved reactions depending on producer gas composition and process conditions:

$$CO + 3\,H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H_R^0 = -206\,\frac{kJ}{mol} \qquad (reaction\ 3)$$

$$2\,CO \leftrightarrow CO_2 + C \qquad \Delta H_R^0 = -173\,\frac{kJ}{mol} \qquad (reaction\ 4)$$

$$2\,CO + 2\,H_2 \leftrightarrow CH_4 + CO_2 \qquad \Delta H_R^0 = -247\,\frac{kJ}{mol} \qquad (reaction\ 5)$$

$$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O \qquad \Delta H_R^0 = -165\,\frac{kJ}{mol} \qquad (reaction\ 6)$$

Except for reaction 1, all the described reactions in the methanation process are exothermic, and it is a well known fact that the process is favoured by low process temperatures and high process pressures.

The last step in the SNG production process is a fuel upgrading. The first and foremost purpose of this step is to meet the quality demands of the gas grid where SNG is introduced. This step primarily consists of removal of unwanted quantities of water, CO_2 etc. (Kopyscinski, et al., 2010).

More details on the methanation process and other steps in the SNG-production will follow throughout the remainder of the report. For the time being the above is assumed sufficient for understanding the basic principles of the procedure.

2.2 Requirements in the Danish natural gas grid

Substituting natural gas with SNG in the Danish natural gas grid poses a series of challenges in relation to gas quality and gas standard. Before assessing the possibilities and limitations of different gasifiers, methanation processes and gas upgrading systems, it is, therefore, essential to review the requirements and standards of the present grid.

For the Danish natural gas grid, some of these characteristics and requirements are listed in Table 2-1 below (Sikkerhedsstyrelsen, 1991).

Table 2-1: Gas quality requirements in the Danish natural gas grid

Gas characteristic	Required value or span of values
General quality requirements	The gas must be clean of all compounds (gaseous, liquid or solid) that can cause blocking, malfunction or corrosion of grid installations and equipment.
Hydrocarbons	The concentrations of unsaturated and aromatic hydrocarbons must be kept at a minimum and must not be allowed to condensate. The hydrocarbon dew point must be below -5 °C at operating pressures of up to 4 bar, and below 0 °C at higher operating pressures.
Water content	Should be kept low to avoid creation of hydrates and corrosion. Water dew point in gas above 4 bar pressure must be below 0 °C. At pressures below 4 bar, the water dew point must be below ambient temperature. If there is a risk of condensation, water collection must be installed in the pipes.
Dust	Must be removed
Sulfur compounds	Due to the risk of corrosion, the total amounts of sulfur and hydrogen sulfide must be limited. However, odorants must be present at minimum values. Limit values are: H_2S: < 5 mg/m^3_n Odorant: THT: 10.5 mg/ m^3_n Mercaptan: 4.0 mg/ m^3_n Other S-compounds: < 10 mg/ m^3_n
Wobbe index (heat effect on gas burner)	Under normal conditions: 51.9-55.8 MJ/ m^3_n
Relative density (dry gas relative to dry air)	< 0.7

The quality of the domestic natural gas resource is very high and changes in the gas characteristics are very limited. This makes it difficult to find supplements of equal quality and stability.

However, energinet.dk is testing physical import of natural gas from Germany now and in the near future (2010-2011) as backup for domestic production, and as supplement if commercial interests in expansion are present. The gas has to comply with the requirements given above, but will not have the same characteristics as the gas from the North Sea (Bruun, 2010).

Many gas characteristics are embedded in the two parameters Wobbe index and relative density. To understand what these characteristics are composed of, the average composition, heating values etc. of the natural gas in the Danish grid from 2010 is presented below. Gas from other sources can be expected to have somewhat similar characteristics on an overall level, but they will often differ significantly on specific parameters. The average values in Table 2-2 are from January to July 2010 (Energinet.dk_A, 2010).

Table 2-2: Average quality of natural gas from the North Sea January – July 2010 (Energinet.dk_A, 2010)

Characteristic	Unit	Average value	Minimum value	Maximum values
Methane content	Mol %	90.08	88.46	91.72
Ethane content	Mol %	5.64	4.90	6.40
Propane content	Mol %	2.15	1.59	2.73
I-butane content	Mol %	0.37	0.33	0.40
N-butane content	Mol %	0.53	0.44	0.62
I-pentane content	Mol %	0.13	0.11	0.16
N-pentane content	Mol %	0.08	0.07	0.10
Hexane+ content	Mol %	0.06	0,.04	0.08
Nitrogen content	Mol %	0.30	0.27	0.32
CO_2 content	Mol %	0.65	0.41	1.01
Higher heating value	kWh/m^3_n	12.109	11.947	12.270
Higher heating value	MJ/ m^3_n	43.593	43.009	44.172
Lower heating value	kWh/m^3_n	10.950	10.797	11.100
Lower heating value	MJ/ m^3_n	39.419	38.869	39.690
Wobbe index	kWh/m^3_n	15.257	15.208	15.318
Wobbe index	MJ/ m^3_n	54.925	54.749	55.145
Normal density	Kg/ m^3_n	0.8144	0.7980	0.8300
Relative density	-	0.6299	0.6170	0.6420
Methane number	-	72.8	70.7	75.3
H_2O dew point	°C	-32.0	-35.9	-28.2
HC dew point	°C	-13.2	-16.5	-9.5
Hydrogen sulfides	mg/ m^3_n	2.4	1.3	4.8
Sulfur total	mg/ m^3_n	2.5	-	-
CO_2 emission factor	Kg/GJ	56.70	56.33	57.03

With the described set of requirements and a high gas standard, it is obvious that not all gasifiers, methanation processes and biomasses can be equally suited for Bio-SNG production. The produced gas can have characteristics that can damage the grid installations, be harmful to personnel or end consumers, or have a quality which makes it unfit to trade and use like natural gas. To match the high Wobbe index, for instance, it is very important to have low concentrations of incombustible gases like CO_2 or N_2. These gases will have to be avoided or removed in the production process to give usable SNG. To help maintain the required Wobbe index, it can be useful to supplement the gas production with a specified amount of a highly combustible gas like propane. This approach is often used when upgrading biogas to SNG quality for use in natural gas grids (Jensen, 2009).

There are many process considerations to be made in this regard, and some of them will be addressed in section 3 of this report. Prior to this, it is, however, important to regard the present gas infrastructure in Denmark to get an understanding of how gas is transported, distributed and used within the system.

2.3 Danish natural gas infrastructure and consumption

When evaluating the possibilities and potentials of introducing SNG in the Danish natural gas grid, it is essential to make a preliminary assessment of the existing system - including the present use of natural gas, the gas infrastructure, the end-consumers and the long-term visions.

2.3.1 The natural gas grids – infrastructure and owners

In July 2010 all natural gas in the Danish grid is supplied from sites in the North Sea, or from storage facilities in Jutland.

The gas is transported through large steel pipes in the transmission grid from the production sites to measurement and regulator stations (M/Rs) in Jutland, Funen and Zealand. The pressure in the transmission grid is up to 80 bar. The transmission grid is owned and governed by energinet.dk.

The M/R stations connect the transmission grid to various allocation grids, and in addition to reducing the pressure from 80 to 50, 40 or 19 bar and acting as potential seal off point for security they are also used for accounting sites. The M/R stations are thus used for gas trading between energinet.dk who owns the transmission grid, and the four different distribution companies who own the allocation grids and distribution grids (DONG Gas Distribution, HMN Naturgas, Naturgas Fyn Distribution and the municipality of Aalborg – Gas delivery).The allocation grids transport the gas through smaller steel pipes to new M/R stations in areas with industry, housing or power production. In these M/R stations the pressure is lowered to 4 or 7 bar. From here the gas is transported through plastic pipes through the distribution grids and to the end consumers in industry, housing or power production.

There is a total of around 4,000 km steel pipes and 14,800 km plastic pipes for transmission and distribution of natural gas in Denmark in 2010. The Danish natural gas grid is connected to the European grid for trading and security purposes (Naturgasfakta.dk_A).

In 2004 the natural gas delivery marked was liberalized so that consumers could freely choose between different distributors. In the beginning of 2005 there were 10 authorized gas delivery companies in Denmark, and today there are 11 where 9 of the 11 delivery companies are owned by the four distribution companies and the last two are OK a.m.b.a and Shell (Energinet.dk_B). It is possible for anyone in Denmark to start delivering natural gas to end consumers as long as there is a written agreement with one of the distribution companies, following the relevant guidelines (Energinet.dk_C, 2008).

2.3.2 Natural gas consumption

In 2009, natural gas covered 20 % of the total Danish energy consumption with 165 PJ out of a total of 810 PJ (Energistyrelsen, 2010). The grids deliver gas to more than 360,000 different costumers, and the gas was used within all energy consuming sectors except for transportation. The main part of the gas is used for heating of individual houses, power production in gas boilers and gas engines of all sizes, for industrial and commercial purposes or traded to Sweden and Germany. Almost half of the Danish population receives their heat either directly or indirectly from natural gas (Naturgasfakta.dk_B). A part of the gas is also used for small gas appliances – like water heaters or open air stoves in Danish cities (Copenhagen, Frederiksberg and Aalborg) with a total around 230,000 costumers. In Copenhagen and Aalborg the natural gas is mixed with air to reach a quality similar to the old fashioned town gas (Naturgasfakta.dk_C).In 2008 the total use of natural gas in Denmark was divided as shown in Figure 2-2 below:

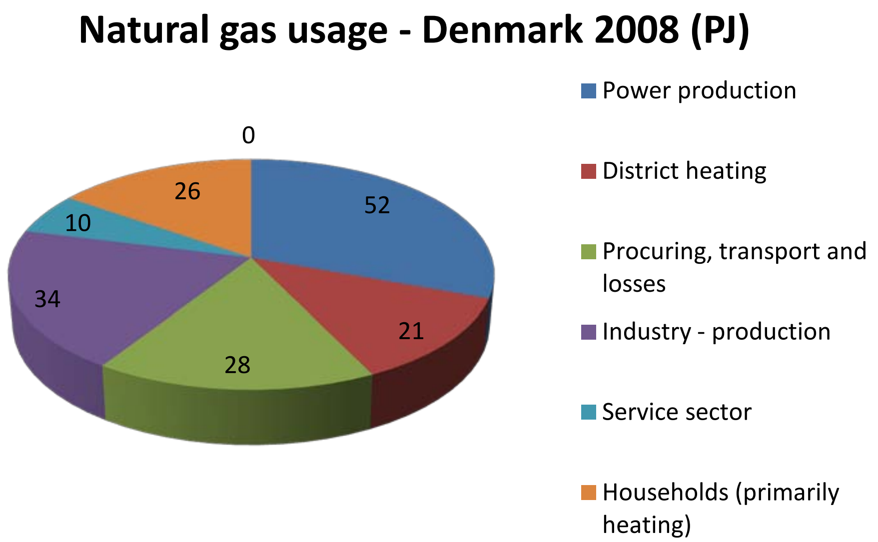

Figure 2-2: Total use of natural gas in Denmark 2008. The power production yielded 25 PJ electricity and the district heating production gave 36 PJ heat for consumption (Energistyrelsen, 2009)

The fastest growing sector in Danish natural gas consumption is power production. Coal and oil is being replaced with natural gas in more and more power production facilities. I Denmark there are many CHP plants (Combined Heat and Power) producing both electricity and district heating. Figure 2-3 illustrates the impact on fuel use from the introduction of natural gas in Danish CHP plants.

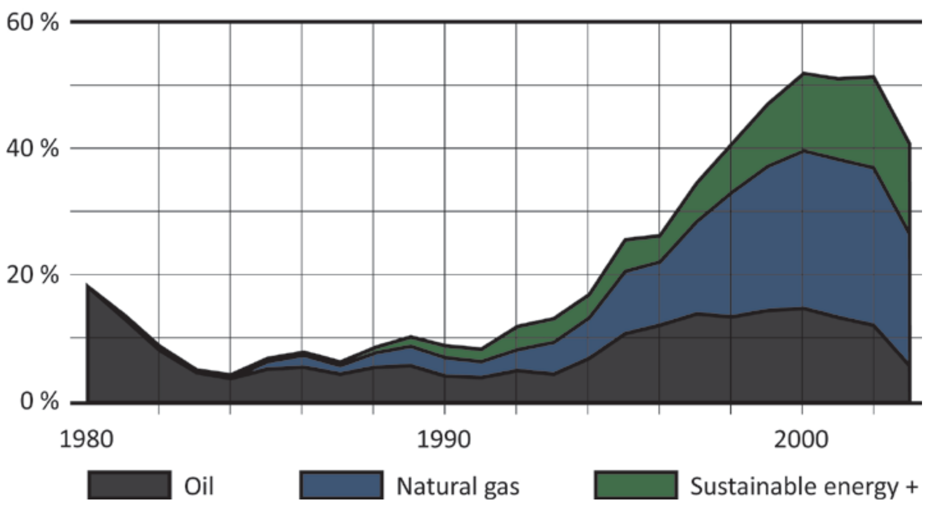

Figure 2-3: Historical view on fuel use in Danish electricity production. Coal is omitted from the diagram and accounts for the missing percentages. The "+" on sustainable energy represents miscellaneous other fuels (Naturgasfakta.dk_D)

De-centralized CHP plants cover 25 % of the total Danish electricity production, and centralized CHP plants cover another 25 %. Almost 80 % of district heating is produced in CHP plants. The total Danish electricity production capacity is almost 7000 MW_e in centralized plants, 1400 MW_e in de-centralized plants and little more than 400 MW_e in industrial plants. 1000 MW_e of this capacity is delivered by 900 gas engines, and more than 50 gas turbines (simple and combined cycle) deliver another 735 MW_e of the country's total capacity (Naturgasfakta.dk_D).

There are significant variations in the predictions about the size of the domestic natural gas resource, but most predictions point towards a self-sufficient production of natural gas somewhere in a time span between 10 and 20 years from 2010 (Naturgasfakta.dk_B; Energistyrelsen, 2008).

2.3.3 Natural gas as transportation fuel

On the "Worldwide NGV statistics" for July 2010, presented monthly in the Gas Vehicles Report by NGV Group, Denmark is not listed with a single natural gas driven vehicle among the almost 80 countries represented with everything from 1 to 2,500,000 natural gas driven cars, buses, trucks and other vehicles (NGV_Group, 2010). Out of a total of more than 11.5 million vehicles worldwide, other countries close by are represented with 376 vehicles in Norway, 23,125 vehicles in Sweden and 85,000 vehicles in Germany. Pakistan is world leader in natural gas driven vehicles with 2,450,000 cars, 100 buses, 50,000 other types and 3,300 filling stations (NGV_Group, 2010).

The growth rate of NGVs in Europe and the world is very high, and new technology and political pressure push the development and expansions in number of filling stations and vehicles. As an example there were 1,200 NGVs in Germany in 2002, 25,000 by the end of 2004 and as mentioned 85,000 in July 2010. With the present growth rate there will be around 200,000 NGVs in Germany by 2020 (Naturgasfakta.dk_E).

In France the focus is on NGVs as commercial or public fleets, and in Sweden the focus is strongly on buses and trucks. The lesson from expansion of NGV fleets in most countries is that the infrastructure and thus the number of filling stations must advance before the number of vehicles will do the same.

In an EU action guideline from 2001: "Promotion of bio-fuels and other alternative fuels for road transportation" measureable goals for NGV acceptance are set as (Naturgasfakta.dk_E):

2010: 6 % biofuel and 2 % natural gas
2020: 8 % biofuel, 10 % natural gas and 5 % hydrogen

In addition the white book aims towards 6 million NGVs in Europe by 2020.

In Denmark the focus on NGVs has been insignificant, and the few tests and trials that have been conducted (company fleets, city buses) have proved the use of natural gas for transport troublesome and problematic – at least for the time being. Interested parties suggest that the main problem is a lack of will to succeed, and that all foreign experience shows a requirement for patience and an acceptance of beginner flaws before development can progress positively (Naturgasfakta.dk_E).

There is not much political focus on natural gas for transportation at the moment, but the matter is briefly mentioned in the Energy Strategy towards 2025.

3 The present state of SNG/bio-SNG

The aim of this chapter is to give specific examples of gasification and methanation technology for SNG production. In addition, this chapter seeks to identify some of the key stakeholders on the SNG scene – including governments, research institutions and commercial partners. Finally, an overview of present and planned SNG-production facilities is used to estimate the worldwide SNG capacity and planned expansion.

3.1 Specific gasification processes for SNG/bio-SNG production

Synthetic substitutes for natural gas have been produced from coal on a commercial scale since The Great Plains Synfuels Plant by the Dakota Gasification Company began production in 1984 with a subsequent capacity of 4.8 Mio m^3 of SNG per day ever since (GPGP, 2006). Before the production in Dakota began, almost 20 years of research and testing had been conducted – funded by frontrunner governments in America, Great Britain and Germany. The political will to engage in this new energy technology came from awareness on the rapidly increasing consumption of natural gas and a focus on the domestic American coal resources, which are supposedly the largest in the world. The engagement was further strengthened by the oil crisis in the 70s (Kopyscinski, et al., 2010). The Great Plains Synfuels Plant is today still the only full commercial-scale plant producing SNG in America.

As with the Great Plains Synfuels Plant, most plants and technologies for SNG production have been developed for coal, lignite or other fossil carbon sources. Today, SNG production is about more than energy security, and in combination with climate change mitigation strategies it is, therefore, more politically appealing to regard technologies that address this double-faced challenge. This is done by exchanging coal fired power plants with Coal-to-SNG processes with CCS potential, or in plants that can convert biomass or waste to bio-SNG. Fortunately, many of the design considerations and unit operations are somewhat similar. Therefore, historic research for one feedstock can now be utilized to some extent for production from other feedstock. However, there are still some challenges to encounter when transitioning from SNG to bio-SNG production. On the one hand, the variations in feedstock from biomass or waste give different chemical compositions and impurities in the producer gas - such as organic sulfur, which can pose new requirements for process robustness or gas cleaning. On the other hand the smaller unit size that is often requested on local or decentralized scale makes it difficult to achieve the same efficiencies (Kopyscinski, et al., 2010).

3.1.1 State-of-the-art SNG production from coal I: Kentucky NewGas

In Kentucky, USA the energy alliance Peabody and ConocoPhilips has recently been granted an air draft permit for the large coal-to-SNG plant Kentucky NewGas. The permit was issued at the end of December 2009, and this initiated the construction of the new plant in Muhlenberg County near the central city of Kentucky (ConocoPhilips_Peabody, 2009).

Kentucky NewGas is planned as a mine-mouth project with almost zero feedstock transportation and operation on bituminous coals, lower-rank coals and petroleum coke from local sites. The plant is expected to consume around 3.5 million tons of coal and produce 60-70 billion standard cubic feet of SNG every year, equivalent to the heating of 750.000 American homes or 30 % of the natural gas consumption in the

Kentucky (coalgasificationnews.com_A, 2009). Using estimates of 32 MJ/kg coal/lesser coal/Pet coke and 1000 BTU/SCF[1] SNG, the coal-to-SNG efficiency of the process is around 60 %. Some of this lost energy is used to run the facility itself. Heat from the gasification reaction is used to produce steam that drives a 250 MW steam turbine. The electricity is then used to power the process, mine and coal conveying.

The Kentucky NewGas plant is to be built with ConocoPhilips E-Gas proprietary gasification technology. In this gasification process the coal is ground into small particles and mixed with water to produce slurry. The coal slurry is pumped into a two-stage entrained-flow gasifier reactor with co-feeding of pure oxygen for partial oxidation under intense heat and high pressure. Coal, water and oxygen are converted to a producer gas that consists primarily of carbon monoxide and hydrogen. Slag is removed from the reactor and used for construction materials. After removing impurities from the producer gas (mainly CO_2, particles, ammonia and sulfur compounds) and adjusting the hydrogen/carbon monoxide ratio, a methanation process (HaldorTopsø's TREMP® Technology) converts the gas stream into a product stream of mainly methane. ConocoPhilips has been developing and testing the E-Gas process for around 15 years. The various steps in the process as well as key contributors to the specific steps are illustrated in Figure 3-1.

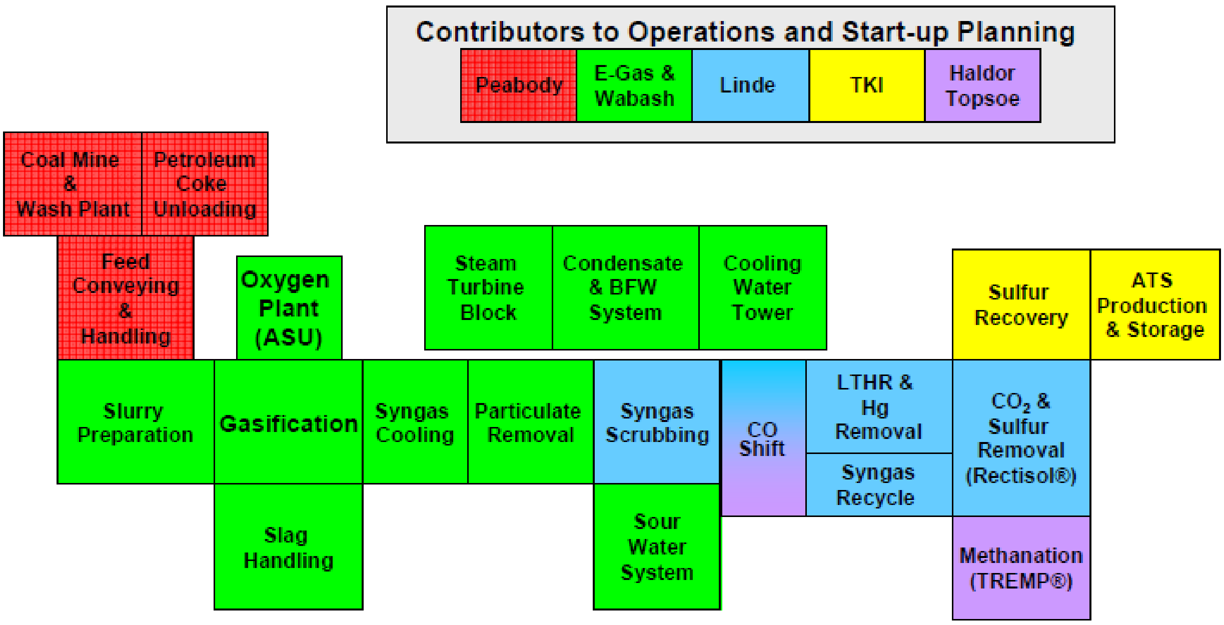

Figure 3-1: The Kentucky NewGas Coal-to-SNG process plant with relevant contributors (Keeler, et al., 2009)

ConocoPhilips argues that the Kentucky NewGas plant will emit around 5 % of the sulfur and nitrogen oxide emissions from a comparable traditional coal plant, remove 95 % of the mercury in the coal cost-effectively, turn 99 % of the sulfur and most of the ammonia into fertilizer and use all remaining by-product stream for construction materials. The companies involved are also deeply engaged in CCS technology/CO_2 pumping in oil fields, and have ambitions to use the area near the Kentucky NewGas for large-scale sequestration of CO_2 from the E-Gas process (coalgasificationnews.com_A, 2009; Keeler, et al., 2009; kentuckynewgas.com, 2009; conocophilips.com).

[1] British Thermal Units / Standard Cubic Feet equals approximately 37,2 MJ/ m^3_n

3.1.2 State-of-the-art SNG production from coal II: C-change and Texas Syngas/NC 12

Another American state-of-the-art SNG-from-coal plant under construction is a 250 billion SCF SNG/day plant in Louisiana. Construction is planned to end in 2012, and in 2010 the first phase is completed and ready for initial testing. The plant is a mine-mouth plant at 4500 feet elevation that will run on a variety of coal resources from high-end coal over PET coke to lignite and has a simulated plant capacity of 706 MW_e based on 3 Siemens 501F gas turbines in combined cycle. The net efficiency of the plant is assumed to be 49 % based on Higher Heating Value calculations (coalgasificationnews.com_B, 2009; Kopyscinski, et al., 2010; Shelledy, 2006).

The plant is based on a liquid metal catalytic reactor which is manufactured in one-size and connected in series for improved capacity. The patents for the technology were bought from an MIT[2]-originated company started by a PhD student in connection to his work in dissimilation of hazardous waste. The original plant was built to neutralize chlorinated hydrocarbons and low level nuclear waste, and the process was efficient enough to neutralize live mortar rounds before explosion reaction could occur. This waste-disposal process was later transformed into a high temperature, commercial gasification technology capable of gasifying a long range of carbon feedstock from waste to biomass to coal and PET coke. Despite the variations in applicable feedstock, large scale projects have been focused on gasifying coal, where gasification of waste and biomass has been used mostly for PR. The liquid metal catalytic reactor used in the Louisiana SNG plant is depicted in a first generation version in Figure 3-2.

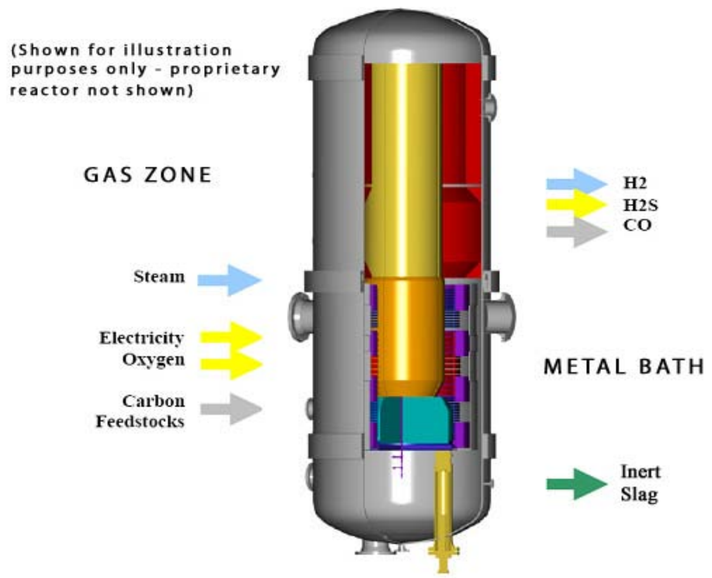

Figure 3-2: Texas Syngas/NC 12 liquid metal catalytic reactor for SNG production (txsyn.com_A)

The Texas Syngas/NC 12 SNG reactors measure approximately 10 feet in diameter, are approximately 10 m high and initiates the gasification process with temperatures around 1500 °C. The process is started with electricity for induction heat generation but as gasification reactions begin to occur, the exothermic nature of the CO reaction supplies more and more of the required energy. Under continuous conditions the reaction produces enough heat to generate steam for simultaneous electricity production.

[2] Massachusetts Institute of Technology

Pure oxygen is used as gasifying agent in the process, and the producer gas is both well defined and suitable for methanation. A process on 50 % Pittsburgh No. 8 (coal) and 50 % Petroleum Coke yields the gas composition given in Table 3-1. Gas composition is compared to published information (TEPPS, 2002) from the Tampa Electric Polk Power Station IGCC. This facility uses an entrained-flow gasifier for gasification of the same feedstock blend and is, therefore, fairly comparable.

Table 3-1: Gas compositions from the Texas Syngas/NC reactor compared to gas from an entrained-flow gasifier (Shelledy, 2006)

Gas component	Unit	TXSG	Tampa (GE)
H_2	Volume %	42	34
CO	Volume %	57	48
CO_2	Volume %	-	14
N_2	Volume %	< 1	3
Other	Volume %	1	1

The proposed gas composition from the Texas Syngas/NC 12 reactor is delivered by the company and not from published information. It has not been possible to find a complete plant design for the Louisianan SNG plant, but the concept is illustrated in Figure 3-3 through a reference plant using the same processes.

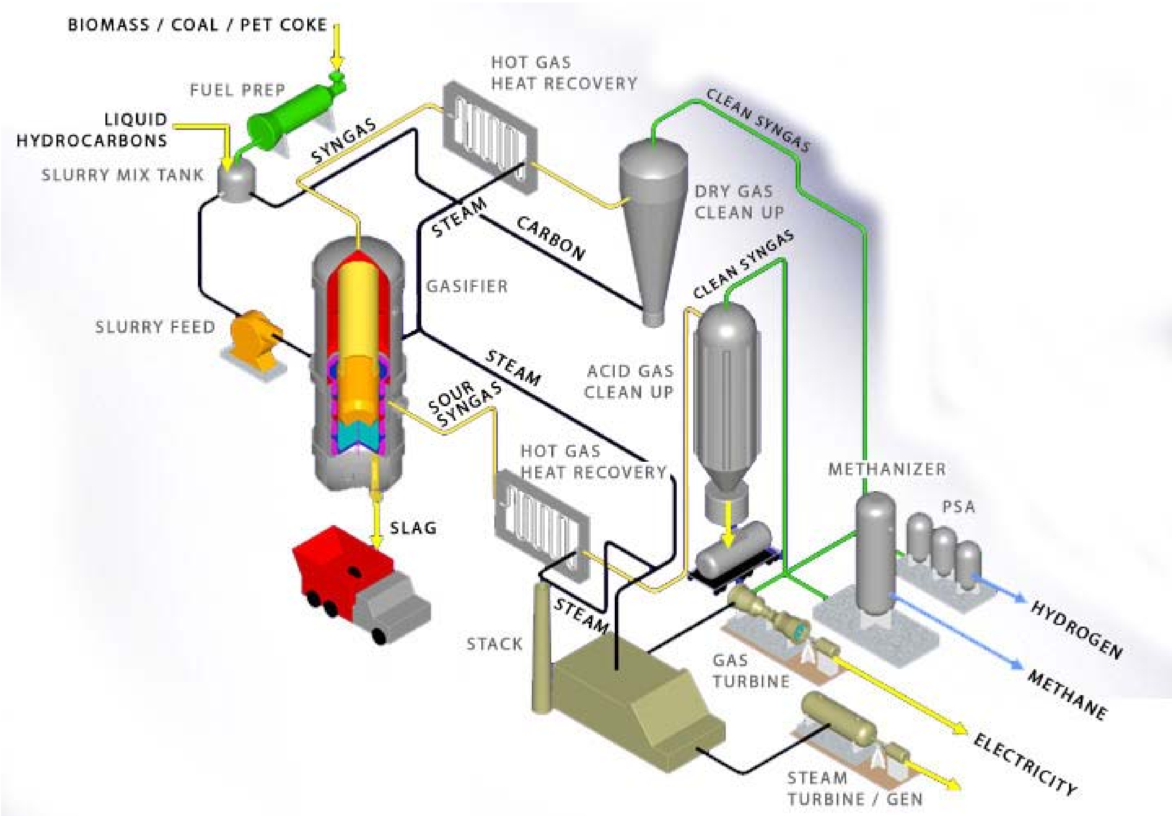

Figure 3-3: Texas Syngas/NC 12 reference plant with liquid metal catalytic reactors (txsyn.com_B)

3.1.3 SNG-from-Coal projects – running and under construction

With large coal resources, especially the Americans are progressing on the planning and construction of new SNG plants running on coal. However, there are also other countries that are initiating or expanding their capacity in the sector. In Table 3-2 the worldwide collection of operational and planned SNG-from-coal plants is gathered to the extent possible within the reaches of this report.

Table 3-2: Collection of operational and planned Coal-to-SNG plants worldwide

Project/country	Feed	Mio Nm^3 SNG /day	CO_2 capture	Online	Reference
Kentucky NewGas, US	Coal	4.6-5.4	Yes	?	(kentuckynewgas.com, 2009; Keeler, et al., 2009)
Freeport Plant, US	Petcoke	5.1	Yes	2012	(Quick, 2007; Wallace, et al., 2008)
South Heart, US	Coal	2.8	Yes	2012	(Stiegel, 2009)
Indiana SNG, US	Coal	3.1	No	2011	(Stiegel, 2009)
Scriba Coal Gasification Plant, US	Coal	7.6	No	2010	(Stiegel, 2009)
Lake Charles Cogeneration, US	Petcoke	?	EOR[3] only	2013	(Stiegel, 2009)
Cash Creek Cogeneration, US	Coal	?	EOR only	2012	(Stiegel, 2009)
Lackawanna Clean Energy, US	Coal	2.4	EOR only	2012	(lackawannacleanenergy.com , 2008)
Southern Illinois Clean Energy Center, US	Coal	2.7	No	?	(Stiegel, 2009)
Decatur Secure Energy Systems, US	Coal	1.9	No	2010	(Petrucci, 2009)
Taylorville Energy Center, US	Coal	?	?	2014	(Petrucci, 2009)
Great Plains Synfuels Plant, US	Lignite	4.1	?	1984	(Kopyscinski, et al., 2010)
Southern Illinois Coal to SNG Facility, US	Coal	5.0	Yes	2013	(powerholdingsllc.com, 2008)
Mayflower Clean Energy Center, US	Coal/ Biomass	?		2009	(greatpointenergy.com, 2009)
NC 12 SNG Project, US	Coal	23	No	?	(Petrucci, 2009)
Fuxin Datang Project, China	Coal	10.8	?	?	(CECIC, 2009)
Shenhua SNG Project, China	Coal	5.4	?	?	(CECIC, 2009)
Huayin Electric Power, China	Coal	4.1	?	?	(CECIC, 2009)
Inner Mongolia Coal Chemical Plant, China	Coal	4.3	?	?	(CECIC, 2009)
Hexigten Qi, China	Coal	10.8	?	?	(CECIC, 2009)
Xinwen Mining Industry Group, China	Coal	5.4	?	?	(CECIC, 2009)

In addition, there are indications about planned facilities in Indonesia, Pakistan, Peru, South Korea, India, Canada and Japan/Australia (zeuslibrary.net, 2010), but further details have not been available at this point.

[3] Enhanced Oil Recovery – CO_2 pumped into oil wells to push out additional oil

3.1.4 State-of-the-art SNG production from biomass I: ECN

The Energy Research Centre of the Netherlands (ECN) has been examining and researching the feasibility of bio-SNG production from biomass since 2002. Thermodynamic studies and flow sheet analysis have led to the development of a dual fluidized bed gasifier (MILENA[4]) with gas cleaning (OLGA[5] +), methanation (several options including TREMP™[6]) and SNG upgrade operations (Kopyscinski, et al., 2010). The combined bio-SNG-production developed by the ECN is depicted in Figure 3-4 (van Hal, et al., 2009).

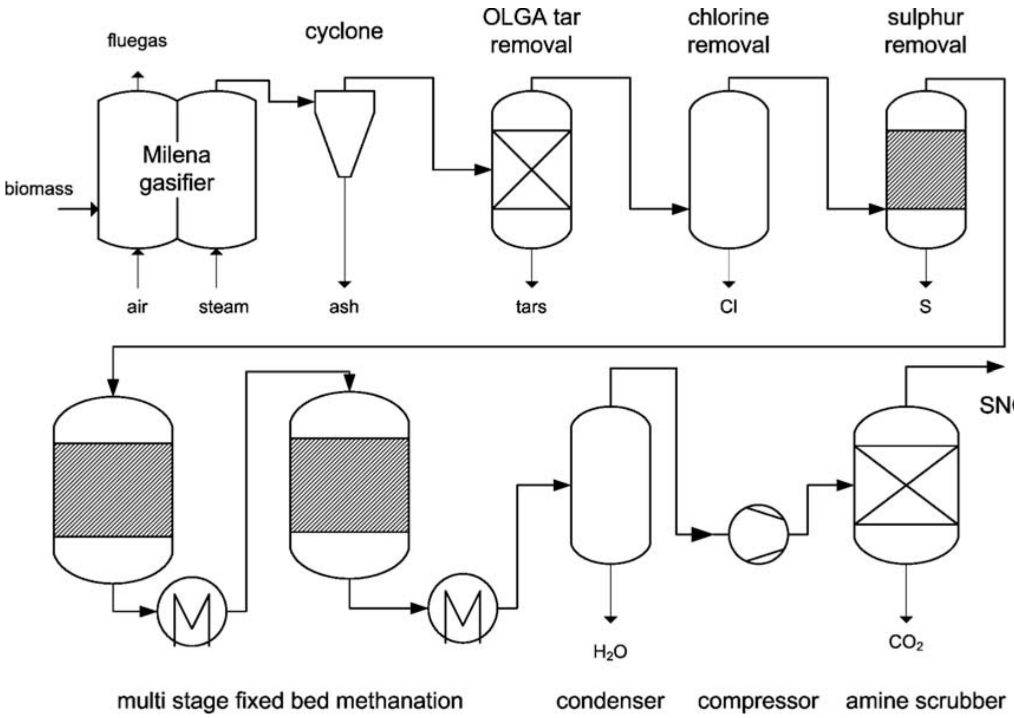

Figure 3-4: Bio-SNG production facility design proposed by ECN (van Hal, et al., 2009)

The twin-bed in the MILENA gasifier consists of a circulating fluidized bed as gasifier and bubbling fluidized bed as combustor. In this way the biomass enters the circulating fluidized bed where it is gasified with steam under heating. The remaining char fraction is then transported to the bubbling fluidized bed where it is burnt with air to produce heat. Finally, the heat is transported back to the circulating fluidized bed for gasification of new biomass. Heat transport is normally done through a bed material like sand. With this display the two beds have separate gas exits, and no nitrogen from the supplied air, or CO_2 from the combustion will dilute the producer gas from the first bed. This is important as it reduces the cost of downstream gas cleaning and upgrading operations, and a high instant methane content in the producer gas increases the biomass-to-SNG efficiency. Instant methane concentrations can be increased by low temperature and high pressure. Twin-bed gasifiers often work at temperatures around 800 °C, which is considered low in biomass gasification. To increase the concentration of methane in the producer gas even further, ECN is testing ways to increase process pressure as well (Bengtsson, 2007).

[4]Multipurpose integrated lab-unit for explorative and innovative achievements in biomass gasification
[5]Oil based gas washer
[6]Topsø's Recycle Energy-Efficient Methanation Process

The gasification in the MILENA gasifier takes place in a riser integrated in the design of the fluidized bed as illustrated in Figure 3-5.

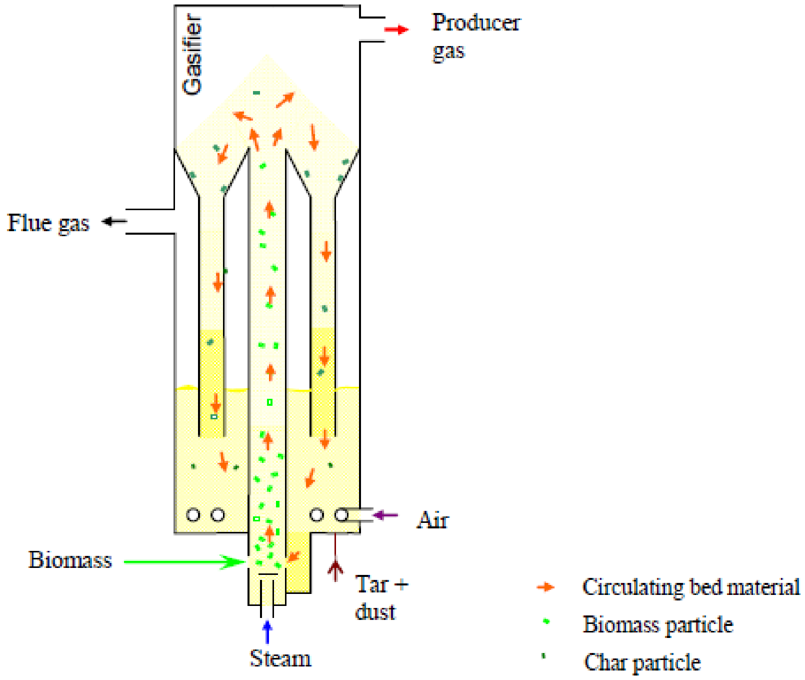

Figure 3-5: Schematic of the MILENA gasifier (van de Meijden, et al., 2010)

According to the developers at ECN, the integrated design of the MILENA gasifier makes it more robust, easier scalable and more suitable for pressurized operations. The gasification of the MILENA gasifier has been validated on wood for several occasions, but tests on grass showed agglomeration problems that have yet to be solved to operate continuously on this feed (Zwart, et al., 2006).

In 2009 it was tested how the MILENA process responded to co-gasifying the biomass with lignite as it is sometimes cheaper than biomass and has some unique features. The conclusion of the tests was that it was definitely possible to co-gasify with as much as 30 wt% coal and that there was a very positive effect on tar production. However, the effect on carbon conversion and sulfur balance was rather troubling, and will require some effort to correct before large-scale co-gasification of lignite with the biomass is feasible (Vreugdenhil, 2009). It has also been tested if the MILENA process can operate on relatively untreated demolition wood, which is a large waste energy source in Holland. Conclusions were that it was possible and gave fine results, but that there were some problems with nails, screws etc. in the feeding system and the ash discharge system, and enhanced pre-treatment of the demolition wood could be the easiest and cheapest way to solve this problem (van de Meijden, et al., 2010).

The gas produced by the Milena gasifier is suitable for application in a gas engine or gas turbine as well as for upgrading to bio-SNG because of the high calorific value of the gas (around 16 MJ/Nm^3 dry, compared to 4-7 MJ/Nm^3 for conventional air blown gasifiers). Another advantage is the complete conversion of the fuel in the twin-bed gasifier compared to typical fuel conversion for downdraft or fluidized bed gasifiers around 85-95 % (van der Drift, et al., 2007).

Composition of producer gas from MILENA gasification of wood is given in Table 3-3 below:

Table 3-3: Producer gas composition from MILENA gasification of wood (Bengtsson, 2007)

Producer gas component (volume %)	MILENA gasification
H_2	18
CO	44
CO_2	11
CH_4	15
C_2H_2, C_2H_4, C_2H_6	1
N_2	4
H_20 (wet basis)	25

Specific gas composition depends heavily on feedstock and process conditions (e.g. temperature (amount of char being combusted), bed material and choice of purge gas (N_2/CO_2)) (Zwart, et al., 2006). Despite specific process conditions, gas cleaning, methanation and upgrading are always necessary to comply with gas quality requirements in natural gas grids. This upgrading process of the MILENA producer gas can benefit from the high methane content and low contents of N_2 and CO_2 (Zwart, et al., 2006). More details on these parts of the process are given in section 3.3 about gas cleaning, methanation and gas upgrading.

The following key characteristics of the MILENA gasifier are from calculations made by Bengtsson, 2007 with a cyclone for particle removal, OLGA tar removal, zinc oxide beds for ammonia and sulfur compound cleaning, three-step TREMP® methanation system, Selexol™ scrubber for CO_2 removal and gas cooling for water removal:

Table 3-4: Key characteristics calculated for MILENA gasification with OLGA tar removal and TREMP methanation (Bengtsson, 2007; van der Drift, et al., 2005)

SNG-process characteristics	MILENA +
Cold gas efficiency (%)	80
Biomass-to-SNG efficiency (%)	66
Overall process efficiency (%)	82
Gas yield (Nm^3/kg biomass)	0.8

The MILENA gasifier began as a lab-scale facility of 24 kW, but the success of the plant has led to the building of a 1 MW pilot plant with gas cleaning, methanation and gas upgrade. The pilot plant was initiated with 150 kg wood/hour in September 2008 with resulting gas composition similar to lab-scale plant. The next step in development of the MILENA gasifier is a 10 MW plant with OLGA tar removal and a gas engine for production of heat and power. This plant is supposed to start operation in 2012, and the process design that it is built on is illustrated in Figure 3-6.

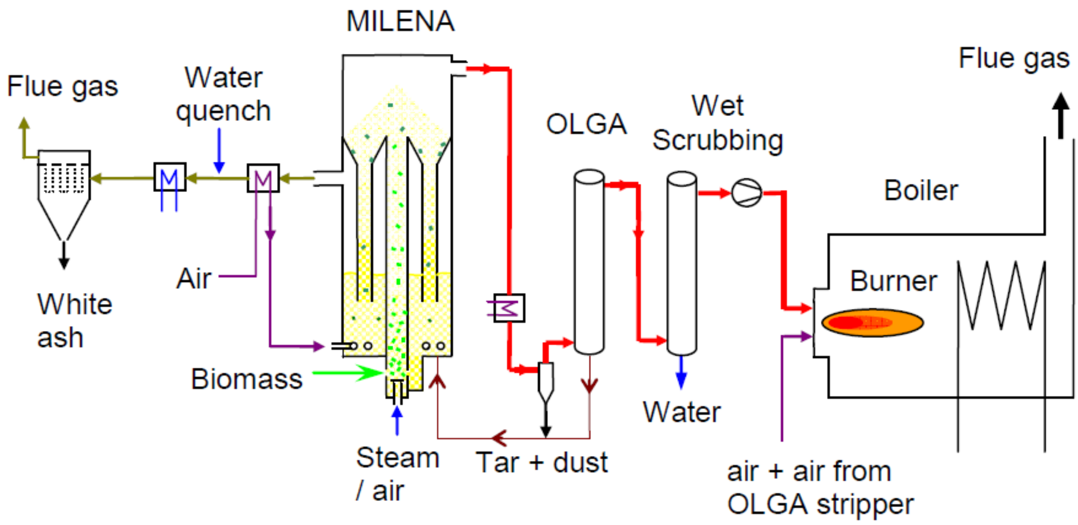

Figure 3-6: Process schematics for a 10 MW biomass gasification plant based on MILENA platform (van de Meijden, et al., 2010)

If the biomass gasifier in the 10 MW scale proves successful, it is to be followed by a complete 50 MW plant for production of bio-SNG using MILENA/OLGA technology. This plant is planned for operation in 2015. The ECN have trust in their technology and have uttered ambitions to scale even larger and complete a 100 MW and a 1 GW bio-SNG facility as well, both based on the MILENA gasification technology and the OLGA tar removal system (van der Drift, et al., 2008).

MILENA 1 MW gasifier, OLGA 1 MW tar removal and the 24 kW systems for further gas cleaning and methanation are displayed in Figure 3-7 (van der Drift, et al., 2009).

Figure 3-7: Picture 1) MILENA 1 MW gasifier. Picture 2) OLGA 1 MW tar removal system.
Picture 3) 30 kW system for additional gas cleaning and methanation (van der Drift, et al., 2009)

3.1.5 State-of-the-art SNG production from biomass II: Paul-Scherrer Institute

In Switzerland, research in the conversion of solid biomass to bio-SNG began 20 years ago and has been carried out intensively since. First the research was conducted by Gazobois SA in collaboration with Ecole Polytechnique Fédérale de Lausanne (EPFL), but for the last 10 years it has been positioned mainly at the Paul-Scherrer Institute (PSI).

The initial research led to a set of technology recommendations in 2002, suggesting the Fast Internally Circulating Fluidized Bed (FICFB) gasification process as the most promising technology for bio-SNG production. This process was developed at TU Vienna, built by Repotec and commercialized in Güssing – all from Austria. The technology was selected because the producer gas is nearly nitrogen free and has high methane contents and because this producer gas has been tested in long-term (> 40,000 hours) industrial tests in a 2 MW_e gas engine (Kopyscinski, et al., 2010).

Based on the work, experiences and recommendations from EPFL, PSI, TU Vienna and Repotec an 8 MW CHP biomass gasifier and a Process Development Unit (PDU) of 1 MW_{SNG}[7] capacity were commissioned. The PDU allows for demonstration of the complete bio-SNG production process including gasification, gas cleaning, methanation and gas upgrade. The first bio-SNG was produced by the PDU in April 2009, and in June the same year the production reached 1 MW_{SNG} equal to 100 m^3/h SNG in H-gas[8] quality (Kopyscinski, et al., 2010). The PDU process schematics are supplied in Figure 3-8.

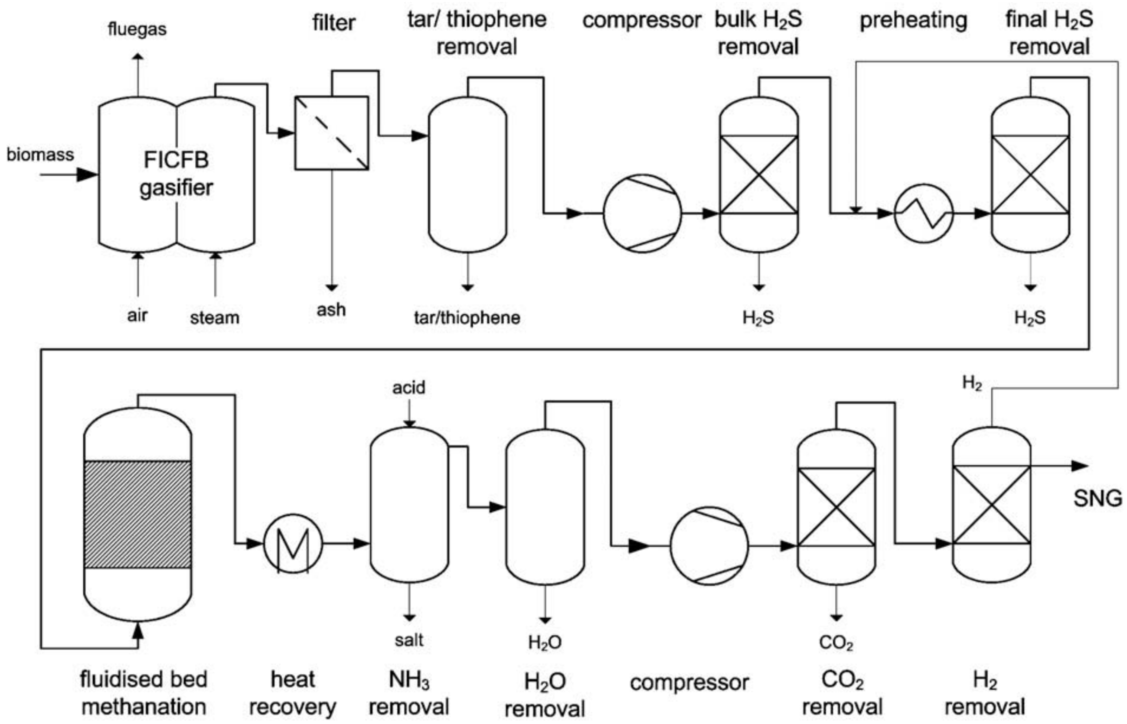

Figure 3-8: Schematics of the 1MW_{SNG} process development unit (PDU) in Güssing (Biollaz, et al., 2009; Kopyscinski, et al., 2010)

[7]Meaning a 1 MW energy content in the bio-SNG flow

[8]Wobbe index 14.0 MJ/ m^3_n and Higher Heating Value = 10.67 kWh/Nm^3

The twin-bed reactor in the FICFB PDU consists of a bubbling fluidized bed as gasifier and a circulating fluidized bed as combustor with a temperature around 850 °C in the gasification zone (Rauch, 2009). This combination has been identified as the most efficient combination of fluidized beds in a twin-bed construction (Xu, et al., 2006). The gas cleaning consists of a filter and a scrubber to remove dust and tars and undisclosed units to remove sulfur components, heavy hydrocarbons and aromatic compounds. Methanation takes place in the PSI/CTU isothermal fluidized bed methanation technology system that enables catalyst stability without upstream ethylene removal or conversion due to internal regeneration of the catalyst (Kopyscinski, et al., 2010). Finally, CO_2, H_2, NH_4 and water is removed/re-circulated before the gas is applicable to the natural gas grid (Rauch, 2009). Average producer gas composition is given in Table 3-5.

Table 3-5: Average producer gas composition of the PSI Güssing PDU (Bengtsson, 2007)

Producer gas component (volume %)	FICFB PDU gasification
H_2	38
CO	23
CO_2	22
CH_4	9
C_2H_2, C_2H_4, C_2H_6	3
N_2	6

The composition shows less CH_4 and CO and significantly more H_2 and CO_2 in the producer gas from the FICFB PDU than from the ECN MILENA. The lesser amount of methane in the producer gas makes the FICFB PDU a less obvious choice for bio-SNG production. However, as it is seen in Table 3-6, the overall efficiency of the complete plant as well as the gas yield is higher in the FICFB PDU than in the MILENA plant.

Table 3-6: Key characteristics calculated for FICFB PDU with fluidized catalyst reactor (Bengtsson, 2007; PSI, 2009)

SNG-process characteristics	FICFB PDU gasification
Cold gas efficiency (%)	55-65
Biomass-to-SNG efficiency (%)	54
Overall process efficiency (%)	97[9]
Gas yield (Nm^3/kg biomass)	1

According to the developers of the PDU in Güssing, the entire process chain reaches high conversion efficiencies and has the potential for lower investment and lower operating cost than conventional SNG synthesis, i.e. fixed bed methanation/BtL[10] technologies (PSI, 2009).

The long-term goal of the Swiss-Austrian consortium behind the plants in Güssing is commercial plants that are expected to be in the scale from 20 to 200 MW_{SNG}. Pictures of the present state of development and construction, the 8 MW biomass gasifier and the 1 MW_{SNG} complete SNG plant, are shown as Figure 3-9.

[9] The very high efficiency is including site-specific district heating production from excess process heat. This is only possible if a district heating grid is present, and, therefore, the overall process efficiency may be significantly lower under other conditions.

[10] Biomass to Liquids

Figure 3-9: Picture 1) 8 MW biomass FICFB gasifier for heat and power production. Picture 2) 1 MW $_{SNG}$ FICFB PUD for SNG production from biomass (PSI, 2009)

The proven gasification technology developed by the Swiss-Austrian consortium and produced by Austrian company Repotec has already been chosen for the large-scale GoBiGas[11] project in Gothenburg, Sweden. The GoBiGas plant is projected as a 100 MW_{SNG} twin-bed FICFB facility that is aimed to turn wood waste (tree tops, roots and branches) into 1 TWh_{SNG} in 2020. The first stage of the project is a 20 MW_{SNG} facility operating in 2012, and then another 80MW_{SNG} facility operating in 2016. Göteborg Energi who governs the project, had done intensive studies of indirect gasification and pressurized oxygen blown gasification, before selecting the twin-bed FICFC platform (Göteborg_Energi, 2009).

The GoBiGas plant will utilize HaldorTopsøe's TREMP™ technology for methanation of the producer gas. Methanation of producer gas from gasified biomass in a plant of this size is presently unheard of, and, therefore, the project will be highly prestigious and the success or failure will definitely influence the future development in bio-SNG production (Marfelt, 2010).

The company behind GoBiGas – Göteborg Energi, owns a 1000 km long, district heating grid that can supply 90 % of all homes in Gothenburg with heat and hot water. In combination with the daughter company Göteborg Energi Gas AB, who owns and controls a natural gas grid in the city, the infrastructure for utilization of the produced SNG is well suited for the task. The 1 TWh of SNG that is the main goal of the GoBiGas plant could replace 30 % of the current natural gas consumption, or fuel almost 75,000 NGVs. In regard to these success criteria, the goal is to reach 65 % biomass-to-SNG efficiency, and overall energy efficiency above 90 %, including production of district heating (Göteborg_Energi, 2009).

[11] Gothenburg Biomass Gasification Project

3.1.6 State-of-the-art SNG production from biomass IV: SilvaGas

The SilvaGas gasifier is a commercially available gasification technology that has been proven on large scale (up to 40 MW) since 1998 and on lab scale for more than 22,000 hours of operation before that. The first large scale SilvaGas gasifier was the Vermont Gasifier that operated from 1998 to 2002 on 200-400 tons dry wood/day, producing gas for the Integrated Gasification Combined Cycle (IGCC) at the McNeil station of the Burlington Electric Department (Rentech, 2009; Bengtsson, 2007).

The demonstration project - the Vermont Gasifier, leading the way for the development of the SilvaGas gasifier - was put together by the U.S. Department of Energy, Battelle, the National Renewable Energy Laboratory (NREL), and Future Energy Resources Corporation (FERCO). In 2009 the SilvaGas concept was bought and developed further by Rentech, inc. (Rentech, 2009).

The thermal conversion process is a low-pressure, indirect gasification of biomass consisting of two circulating fluidized beds with sand as heat carrier. The process mixes wood chips with very hot sand at a gasification temperature of about 830°C. The process is illustrated in Figure 3-10.

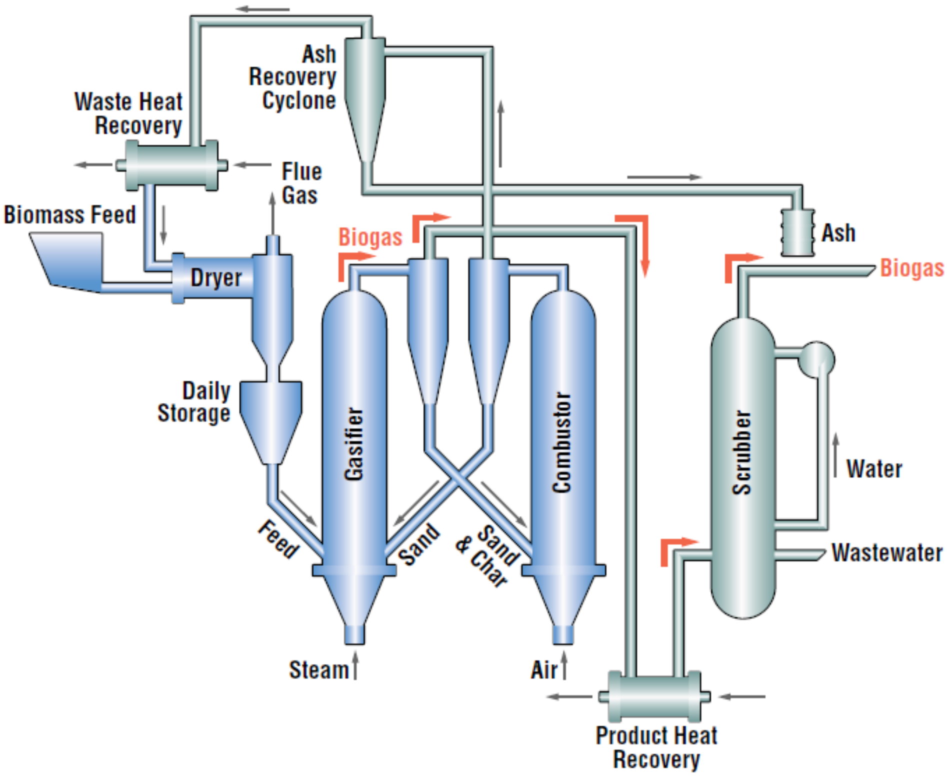

Figure 3-10: The SilvaGas gasification process, illustrated through the Vermont Gasifier (DOE, 2000)

According to the developers the SilvaGas gasifier costs much less to build and operate than other systems, because it is oxygen free, operates under low pressures and processes biomass much quicker than other gasifiers. In addition, the process is very robust, and process restarts can be accomplished within 30-45 minutes. This results in smaller, less costly equipment for a given amount of biomass (DOE, 2000; Paisley, et al., 2002).

Today, the SilvaGas gasifier can be integrated with Rentech's technologies for the production of certified renewable synthetic jet and diesel fuel, or it can produce gas for renewable electric power or synthetic natural gas production. There is a strong focus on liquid fuels, but the Rentech Process is also capable of upgrading producer gas to SNG quality.

The process feedstock can be municipal waste, biomass, coal or PET coke, the catalyst for methanation is iron-based and the Rentech Process uses a slurry bubble column reactor, known as the Rentech Reactor, to turn the producer gas feed into useful products. The gas is fed into the bottom of the reactor where it is mixed with liquid wax and the solid catalyst to slurry. The chemical reactions are exothermic and steam is generated in the internals of the reactor to produce steam and to remove heat. Gas upgrading technology is provided by UOP LLC, a refining and petrochemical process technology company (Rentech, 2009).

The average gas composition for producer gas from a SilvaGas gasification of wood is given in Table 3-7.

Table 3-7: Average producer gas composition of a SilvaGas gasification of wood (Bengtsson, 2007)

Producer gas component (volume %)	SilvaGas gasification
H_2	22
CO	44
CO_2	12
CH_4	16
C_2H_2, C_2H_4, C_2H_6	6
N_2	-

The composition of the SilvaGas producer gas is very much comparable to the composition of gas from the MILENA gasifier. The main difference is a higher content of heavier hydrocarbons in the SilvaGas gas, and the absence of nitrogen in the gas. The gas from the SilvaGas gasification has a medium calorific value with Higher Heating Value around 11-14 MJ/Nm^3 (Paisley, et al., 2002).

The methanation system for the integrated SilvaGas-Rentech Process is built on iron catalyst as described above. However, no detailed information about product or process characteristics is available for comparison with other technology platforms. Table 3-8, therefore, gives the characteristics for a process with the SilvaGas gasification combined with the PSI/CTU methanation system from Güssing.

Table 3-8: Key characteristics calculated for SilvaGas gasifier with PSI/CTU methanation system (Bengtsson, 2007; Rollins, et al., 2002)

SNG-process characteristics	SilvaGas gasification
Cold gas efficiency (%)	36
Biomass-to-SNG efficiency (%)	57
Overall process efficiency (%)	83
Gas yield (Nm^3/kg biomass)	0.8

Combining Table 3-6 and Table 3-8 shows that the SilvaGas process with PSI/CTU methanation does not deliver quite the same high yields or overall efficiency as the FICFB from Güssing with the same methanation process or the MILENA gasifier with TREMP® methanation.

In Figure 3-11, pictures of selected aspects of the SilvaGas-Rentech Process are shown.

Figure 3-11: Picture 1) Vermont Gasifier of the SilvaGas type. Picture 2) Rentech process iron-oxide catalyst. Picture 3) Rentech Reactor for methanation or other fuel synthesis (Rentech, 2009)

3.2 Alternative technology platforms for bio-methane production

Thermal gasification of biomass is not the only way to produce a gas suitable for further upgrading and SNG-production. Biogas from anaerobic digestion of various sorts of waste biomass can reach an overall chemical efficiency around 20-40 % (chemical energy content of biogas compared to the chemical energy input of the feedstock) when further reformed for SNG production (Kopyscinski, et al., 2010). This is not unimportant as it is a process that can handle extremely wet biomass resources in addition to dry ones, and there is a strong political focus in Denmark on production of biogas from anaerobic digestion of pig manure (Klima-&Energiministeriet, 2010). This option is described briefly below together with another technological approach to wet biomass – gasification in a hydrothermal environment (supercritical water, T > 375 °C and p > 220 bar) (Kopyscinski, et al., 2010).

3.2.1 Anaerobic digestion of wet biomass for bio-SNG production

Biogas is produced in an extremely simple process where various cultures of microorganisms digest the labile fractions of organic carbon from waste or other biomass sources under oxygen deprived conditions. The process is very similar to the digestion in the stomach of a cow or pig, and the cultures of microorganisms that are used often originate from pig or cow manure. The biogas production process is very robust, and small variations in process temperature or feedstock will seldom kill the operation, but are more likely just to change the output and efficiency. The main tasks to do when maintaining a biogas production facility are to keep an optimum temperature (around 30-40 °C), stir the tank once in a while, maintain a high liquid fraction and keep a slow continuous flow of fresh feedstock into the facility and indigestible lignin fraction out of the facility. Due to the very few maintenance requirements of a biogas plant, the energy input in the process is very low compared to other methane-production technologies.

In addition to the carbon-neutral energy production from the biogas, the anaerobic digestion has the following benefits when the residual lignin fraction from the process is used for fertilizer compared to direct utilization of manure for fertilizer purposes (xergi, 2010):

- Reduced leaching of nutrients (due to better plant uptake of nutrients)
- Reduced amounts of pathogens (triggers of disease in humans and animals)
- Reduced smell from fertilizer operations

It is also possible to combust or gasify the residual fraction from the biogas process, in order to maximize the energy output. Depending on the technology this would reduce the availability of the embedded nutrients for plants totally or to some extent. To maintain as much availability and as many nutrients as possible, the conversion of the residual fraction should be kept at as low temperatures as possible.

Just as it is the case with producer gas from gasification of biomass, the biogas from anaerobic digestion has to be upgraded to comply with natural gas grid requirements. The main diluting component in biogas from anaerobic digestion is CO_2, and it is also necessary to clean out any harmful sulfur compounds that could otherwise damage equipment or kill catalysts. In Denmark, a filter of active carbon or direct addition of iron salts is usually used to remove sulfur compounds, and CO_2 could be removed with Pressure Swing Adsorption (adsorption of CO_2 under high pressure, and release from coal at low pressure), water scrubbing (high CO_2 solubility and low CH_4 solubility in water under high pressure) or amine washing (chemical sorption at low temperatures -40 °C) (Jensen, 2009).

The standard composition of biogas from manure is 65 % CH_4, 35 % CO_2 and minor fractions of various other compounds. A gas with this composition would have a Wobbe index of 27 MJ/Nm^3, compared to natural gas requirements 51-56 MJ/Nm^3. Pure methane has Wobbe index 53.5 MJ/Nm^3, and to comply with the natural gas grid requirements, the produced bio-SNG would have to be 97.3 % pure methane or higher. If the Wobbe index is too low, propane can be added.

The price on an upgrade to SNG quality has been estimated to be around 0.78-1.13 DKK depending on upgrade technology, plant size, and whether propane is added for securing gas quality or not. The combined set of operations from raw biogas to SNG is estimated to use 4-7 % of the energy in the raw biogas depending on choice of technology (Jensen, 2009). Biogas from manure alone is estimated to cover 3 % of Denmark's energy requirements or 12 % of energy for transport if upgraded to SNG (præmis, 2009).

In 2008 biogas was produced from ca. 4 wt% of the total Danish manure, delivering approximately 1.1 PJ or 0.13 % of the total Danish energy consumption (Energistyrelsen, 2009; Jørgensen, et al., 2008).

3.2.2 Hydrothermal gasification of wet biomass for bio-SNG production

Another approach to SNG production from wet biomass is through a hydrothermal gasification process. The hydrothermal conversion turns wet biomass directly into methane, CO_2 and water in a catalytic process that takes place in supercritical water (T > 374 °C and p > 220 bar/22.1 MPa) (Kopyscinski, et al., 2010).

Converting biomass to SNG in wet environments (biogas/hydrothermal gasification) makes the requirement for drying obsolete. Drying can be very energy intensive and avoiding it can increase the overall process energy efficiency. As methane is a gas that is practically insoluble in water, no energy-intensive separation process is required. However, as the process is often based on the use of catalysts it is important to separate salts from the feedstock as this will prolong catalyst life. Separating salts from supercritical water is less of a task than removing them from sub-critical water. Supercritical water behaves more like an organic solvent than it behaves like sub-critical water, rendering many salts practically insoluble and, therefore, forcing precipitation. Because of this change in the behavior of the water under critical conditions it is possible to introduce efficient and continuous salt separation unit operations in the process. If salt intensive biomass sources – like manure, is utilized in the process, large amounts of concentrated salts will in this way be secured as accessible nutrients for fertilizer production (Luterbacher, et al., 2009; PSI, 2007).

To illustrate some of the possibilities of the hydrothermal gasification process, a simplified process flow sheet is given in Figure 3-12. The flow sheet shows the possibility for utilization of both wood and manure in the process, as well as three different gas cleaning/upgrading systems.

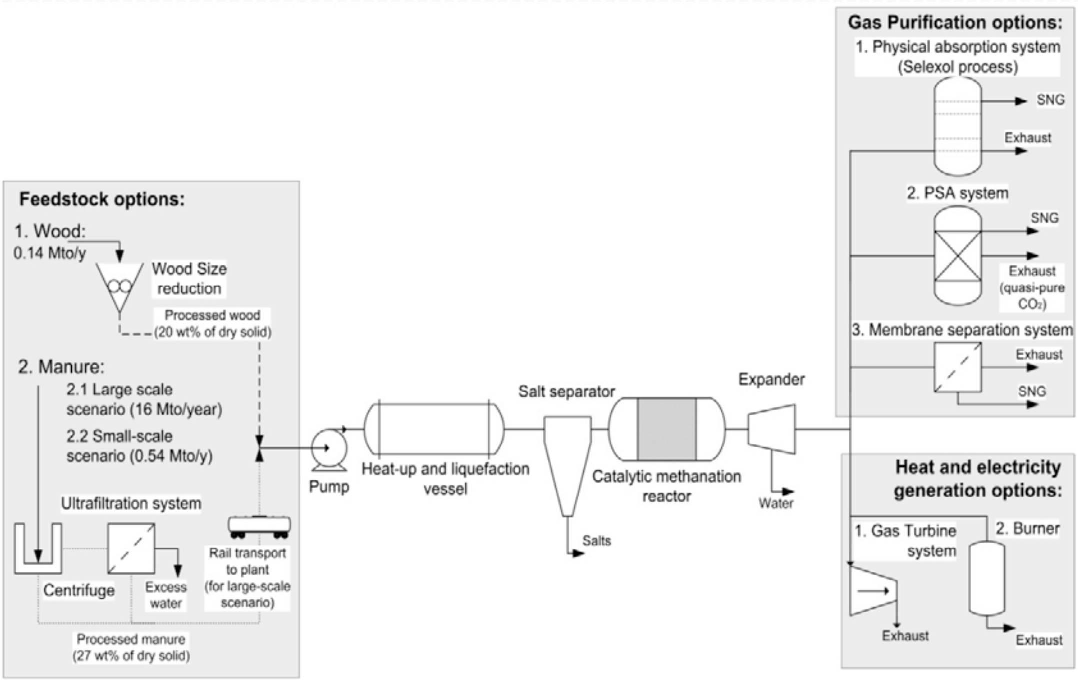

Figure 3-12: Flow sheet for SNG production from hydrothermal gasification of wood/manure (Luterbacher, et al., 2009)

Degradation of biomass in supercritical water has been investigated in America for more than 25 years and in the rest of the world for around 15 years (Elliott, 2008). At the Paul Scherrer Institute (PSI) in Switzerland, research on - and development of - hydrothermal gasification processes from wood, manure and biological waste has been taking place since the beginning of 2000. The institute claims higher process efficiencies than other conversion technologies (up to 70 %), easier CO_2 separation due to solubility in the water at high pressures, and extremely clean product and by-product streams (PSI, 2007). A test series on wood in a small lab scale batch reactor from 2005 gave the results shown in Figure 3-13.The test was done with 10 wt% wood, a Raney Ni 2800 catalyst, a wood/catalyst mass relationship of 2, a temperature of 400 °C and a pressure of approximately 30 MPa (Waldner, et al., 2005).

The left side diagram in Figure 3-13 shows the amount of methane in the produced gas as a function of residence time. It is evident that the process almost reaches the thermodynamic equilibrium for the present temperature and pressure after approximately 25 minutes. HB400NC1 is a setup without catalyst. The right side diagram shows the gasification efficiency (GE) with dark symbols, and the dissolved organic carbon (DOC) in the remaining aqueous phase with white symbols. Additional results from the tests at PSI showed a slight increase in carbon deposits on the catalyst surface during operation. There was no formation of chars or tars during the various tests and operations, and the aqueous phase was clear and colourless. Maximum methane yield was 0.33 gram methane per gram wood (Waldner, et al., 2005).

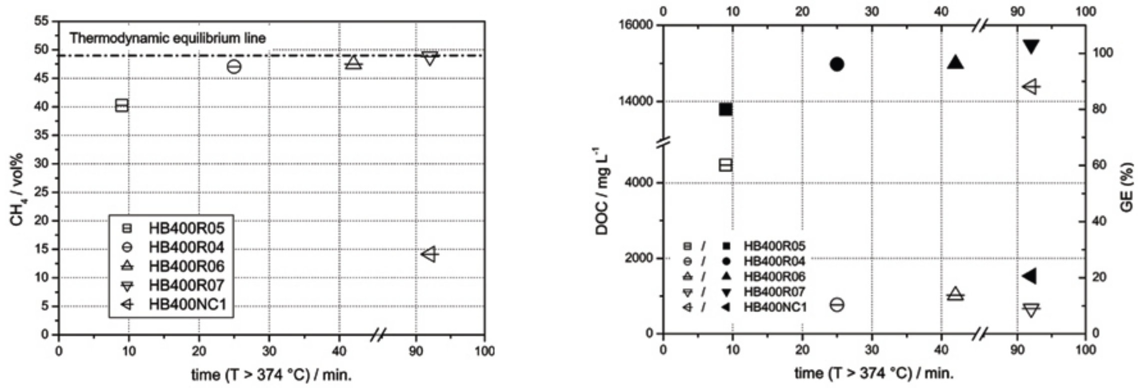

Figure 3-13: Results from a lab scale hydrothermal gasification reactor, converting saw dust to SNG (Waldner, et al., 2005)

The low temperatures of the hydrothermal gasification technologies can prove to be an advantage in bio-SNG production compared to conventional gasification. The two main reasons for this is 1) Great potential for increased thermal efficiency and 2) Formation of methane is favoured by low temperatures and high pressures, where formation of hydrogen is more common at higher temperatures. Despite high conversion rates, the gas from the hydrothermal gasification of biomass need upgrading like biogas from anaerobic digestion or conventional gasification producer gas to reach natural gas grid quality.

In addition to nickel catalysts, other catalytic systems - like ruthenium on carbon or ruthenium stabilized nickel - have been identified as a hydrothermally stable catalyst for the production of methane from biomass in hydrothermal gasification (Vogel, et al., 2007). For a more thorough review on the history of thermal gasification of biomass and the experiences with a long range of different catalysts in the process see Elliott, 2008.

3.3 Methanation and upgrading technology for SNG production

Several commercial technology platforms are available – and in use, for methanation and gas cleaning/upgrading operations in SNG production. Companies like Haldor Topsøe (the TREMP™ process), Linde and Lurgi (the Rectisol® process), Davy Process Technology (DPT - part of Johnson Matthey Plc) have major orders on complete processes and a series of additional companies (like BASF and B&K Technology Group) produce specific catalysts that are usable in the SNG process as well. The TREMP™ and Rectisol processes are presented in the following to illustrate parts of the gas synthesis, clean up and upgrading.

3.3.1 Haldor Topsøe's TREMP™ technology

Haldor Topsøe delivers catalysts and catalysis unit operations for a wide selection of industries. The company has also developed a catalyst technology for use in SNG production. This technology is named TREMP™ - Topsøe Recycle Energy-efficient Methanation Process, and the company claims that it is second-to-none in energy and cost efficiency in SNG production from coal, PET coke or biomass (Topsøe, 2009).

Unit operations upstream from the methanation reactor are highly important to secure a near-stoichiometric ratio of hydrogen to carbon oxides in the gas according to the methanation reactions. Therefore, the TREMP™ system cannot be purchased turnkey, but only as a custom made setup for each specific scenario, thus securing high cost efficiency and gas quality. However, to describe the general context in which the technology is commonly used, the company has supplied the illustration in Figure 3-14. In addition to the gas upgrade in the TREMP™ section, Haldor Topsøe can also provide the WSA unit (Topsøe Wet Sulfuric Acid) for recovery of sulfur from the acid gas removal unit – for example by converting the sulfur to concentrated sulfuric acid, as well as the shift conversion unit integrated to adjust the ratio between hydrogen and carbon monoxide.

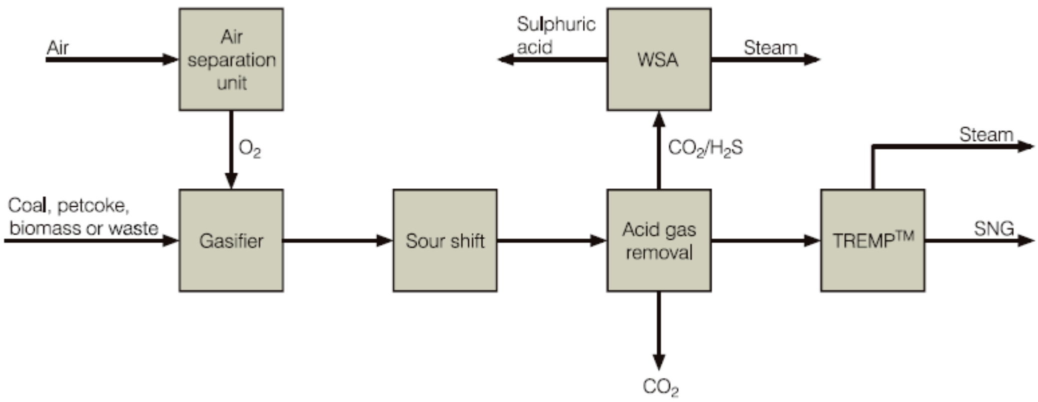

Figure 3-14: Typical plant flow sheet for an SNG production plant with TREMP™ technology (Topsøe, 2009)

The TREMP™ technology is focused on heat recovery from the exothermic reactions of the methanation process. The heat released in this process can amount to as much as 20 % of the total heating value of the producer gas, making it very important to integrate efficient heat recovery to ensure high overall energy efficiency. The TREMP™ technology recovers the heat as high-pressure superheated steam (100 bar g/ 540 °C), which requires the reaction heat to be recovered at a high temperature. Up to 85 % of the reaction heat is usually recovered, amounting to a typical steam production of about 3.0-3.5 kg/Nm^3 SNG (Topsøe, 2009).

TREMP™ is based on the Topsøe MCR methanation catalyst family, which can operate in a temperature range from 250 °C to 700 °C proven for more than 10,000 hours of operation. The large temperature span, in which the catalyst can operate, helps to secure excess reaction heat at high temperatures – leading to high energy efficiency.

A flow sheet of the TREMP^{TM} technology is provided by Haldor Topsøe and is shown in Figure 3-15. The reactions all take place in adiabatic fixed bed reactors. Recycle is used to control the temperature rise in the first methanation reactor, and in order to minimize the energy consumption the process is optimized for minimum recycle. The exit gas from the first reactor is cooled by production of superheated high-pressure steam. The gas then enters the subsequent methanation stages, which are tailored in number and configuration to the specific application.

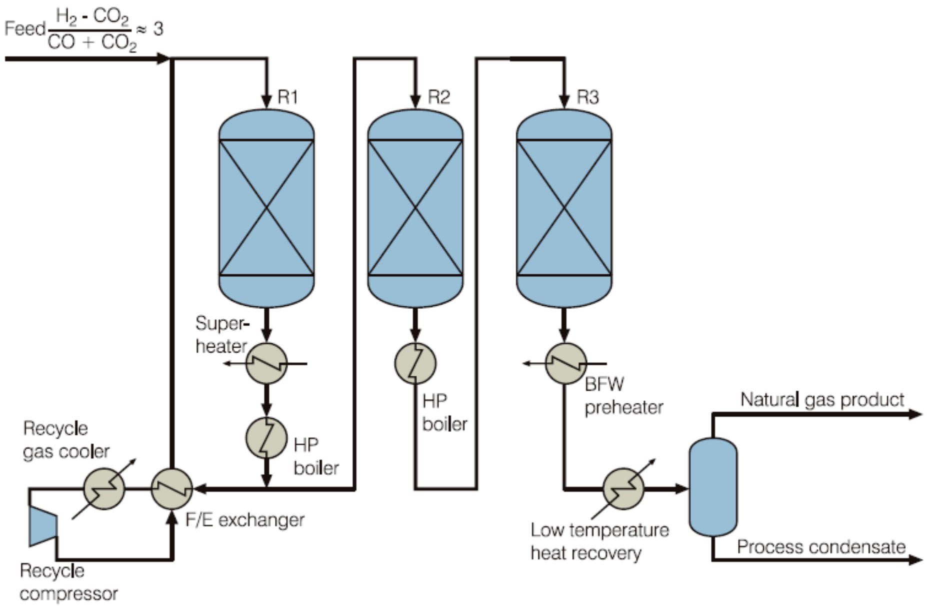

Figure 3-15: Flow sheet example of Haldor Topsøe's TREMP technology (Topsøe, 2009)

Haldor Topsøe commits their TREMP^{TM} technology to produce SNG that complies with all gas grid requirements in a specific context. The product gas usually has a composition as indicated in Table 3-9.

Table 3-9: Normal gas composition of SNG from plants integrating Haldor Topsøe's TREMP^{TM} technology

Producer gas component (mole %)	TREMP average product
CH_4	94 - 98
CO_2	0.2 - 2
H_2	0.05 - 2
CO	< 100 ppm
N_2+ Ar	2 - 3
HHV, MJ/Nm^3	37.4 - 38.4

3.3.2 Linde and Lurgi's Rectisol® process

Rectisol® is a physical acid gas removal process that has been invented by Linde and Lurgi and used in various ways for many years. The process uses an organic solvent (typically methanol) at subzero temperatures to purify synthesis gas down to < 0.1 vppm total sulfur (including COS) and CO_2 to < 10 ppm. The process has some energy efficiency issues due to the cooling of the solvent, but at the same time it is a well proven technology that is highly flexible and used in many different processes.

At the very low temperatures of the Rectisol® process, both carbon dioxide and hydrogen sulfide are very soluble in the liquid methanol. In addition, the selectivity for hydrogen sulfide and carbon dioxide absorption in the Rectisol® wash is very good, which allows for a subsequent sulfur-free carbon dioxide recovery. In this way it is fairly simple to separate the sulfur compounds from the tail gas, thereby making the main exit gas stream consist of mainly N_2 and CO_2 that can be emitted to the atmosphere without further processing (Tunå, 2008). An example of a Rectisol® process flow sheet is given in Figure 3-16.

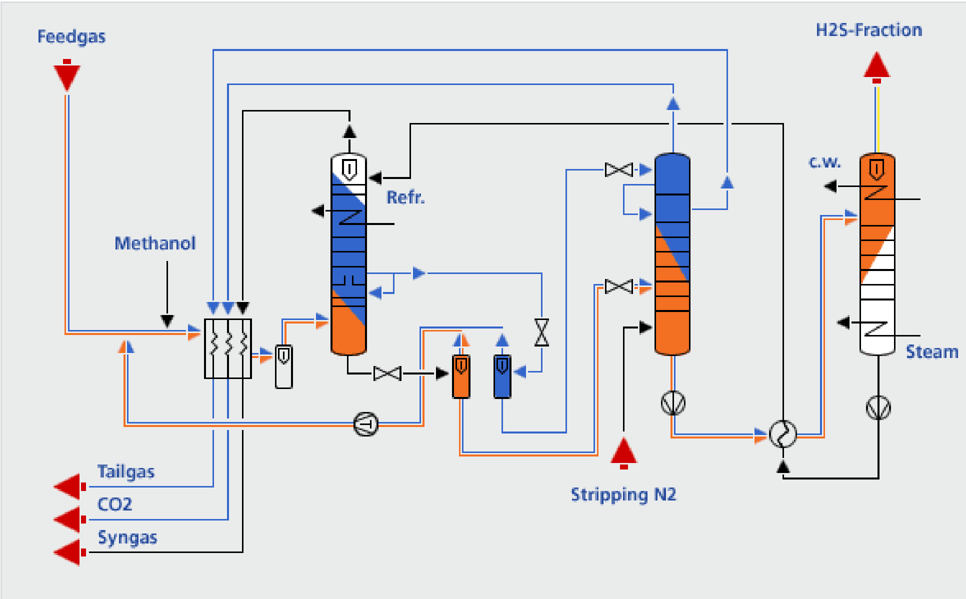

Figure 3-16: Rectisol® process flow sheet example (Linde, 2005)

The Rectisol® process is a wet process with good selectivity and the advantage of hydrogen sulfide and water removal. However, the low temperature operations are energy demanding and thus very disadvantageous for the overall energy efficiency.

The Rectisol® process has no integrated methanation step and is thus integrated only for gas cleaning and upgrading. Integrating the Rectisol® process in a complete SNG production facility could be done as illustrated in Figure 3-17. The Rectisol® process is indicated with a red transparent shape and integrated in the process between gasifier and water-gas shift reactor as well as between the water-gas shift reactor and the methanation process. The methanation could very well be something like an adiabatic reactor in the form of recycle-gas reactors like the TREMP™ process fed around 300 °C, with sufficient cooling/steam generation to keep the temperature within the active span of the catalysts (Tunå, 2008; Topsøe, 2009).

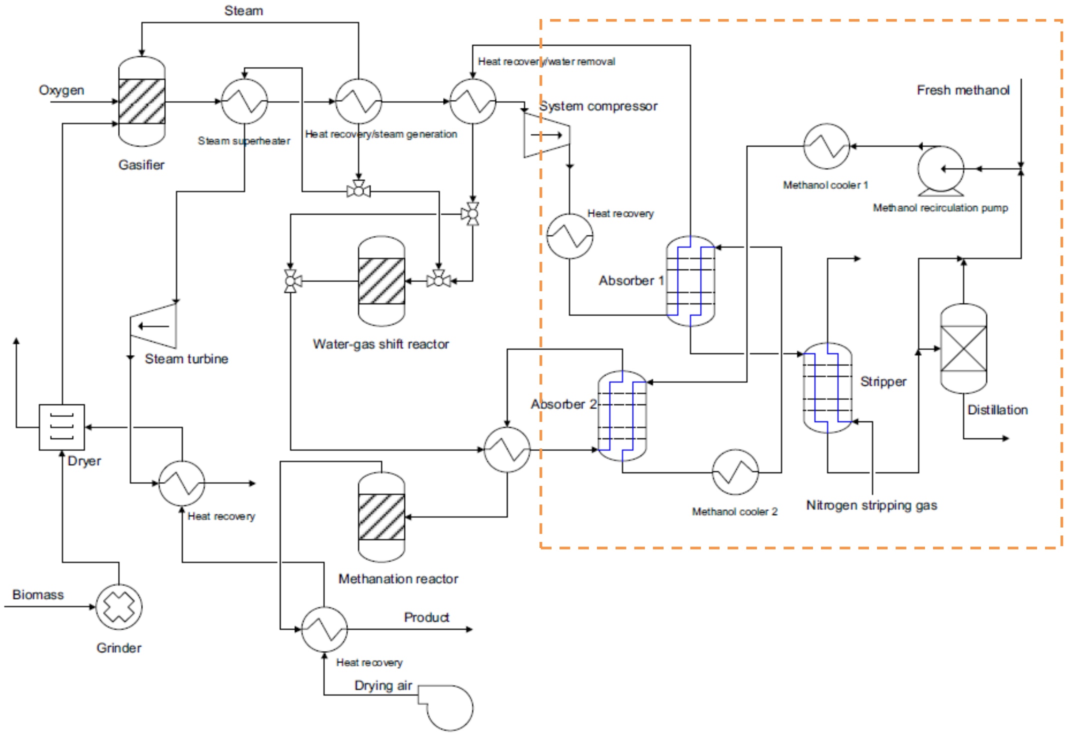

Figure 3-17: Integration of the Rectisol® process (orange marking) in a complete bio-SNG production facility (Tunå, 2008)

3.4 Comparison of selected bio-SNG production plants

Combining different gasifiers, methanation systems and gas upgrading technologies in different ways with various feedstock and process parameters will yield different end products with varying quality and give variations in the overall process efficiency. To illustrate this point an example is given where some of the main characteristics of four different SNG production system combinations are compared and the overall plant suitability against a series of requirements is evaluated. The investigation was done in 2008 by Per Tunå from the university in Lund for the Swedish company Svenskt Gastekniskt Center AB. It was based on a thorough literature review and technology examination combined with detailed mass and energy balance calculations done in Aspen Plus (Tunå, 2008).

The different gasification techniques included in the evaluation are an entrained-flow gasifier, a fluidized-bed gasifier and an indirect gasifier. They are coupled with two different desulfurization systems and two methanation processes. The desulfurization systems were a zinc oxide bed and a Rectisol® wash system. Methanation were performed by a series of adiabatic reactors with gas recycling and by an isothermal reactor. The processes were all modeled with 30 bar pressure and a H_2/CO ratio of 3.

The results of the study show that the fluidized bed and the indirect gasifier have the highest SNG efficiency. SNG efficiency is defined as the energy in the SNG product divided by the total input to the system from biomass, drying and oxygen. SNG efficiencies in excess of 50 % were possible for all gasifiers as indicated in Figure 3-18.

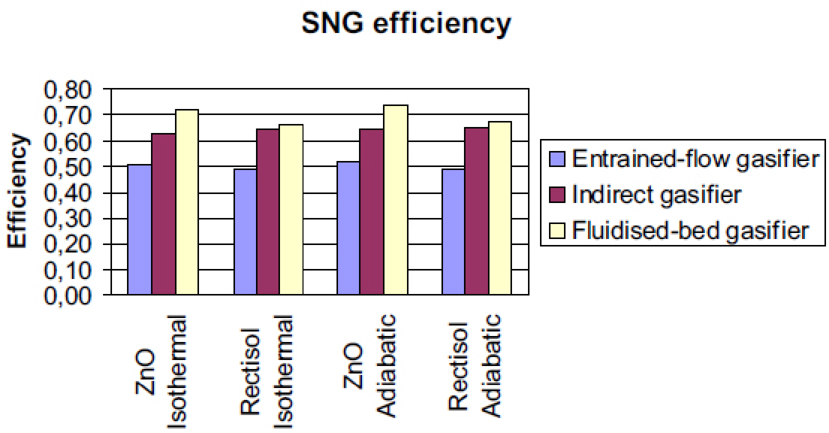

Figure 3-18: SNG efficiency of a combination of different gasifiers, methanation systems and gas cleanup procedures (Tunå, 2008).

Furthermore, the results of the study showed that there were little to no difference between the methanation processes and only small differences for the gas cleanup systems. Increasing the system pressure showed a negative impact on SNG efficiency and increased consumption for compression. The temperature of the isothermal methanation process showed no significant impact on the SNG efficiency, and it was concluded that the recovery of as much methane as possible in the gas upgrade systems (especially the PSA - Pressure Swing Adsorption) is the most important parameter. Recovering methane that has been dissolved in condensed process water increased the SNG efficiency by 2-10 % depending on system.

The energy efficiency of the processes in Figure 3-18 has been calculated as combined losses and uses in percentage of the total output. The losses and uses are the sum of heat loss, energy used for drying, energy used for cooling, energy used for oxygen separation and electricity consumption – where these utilities are used. The results of these calculations are shown in Figure 3-19

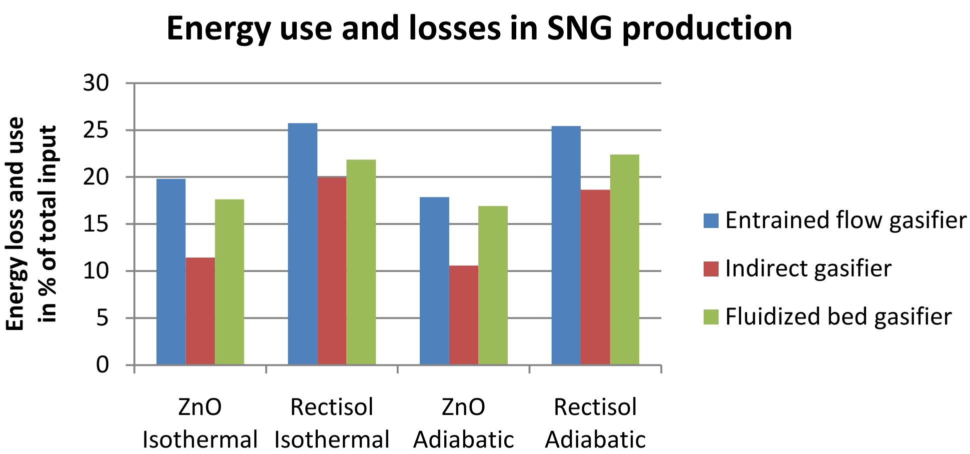

Figure 3-19 : Energy efficiency of 12 SNG production processes. Calculated from data by (Tunå, 2008)

The differences in the diagrams in Figure 3-18 and Figure 3-19 is the production of district heating and electricity in the specific process. The entrained-flow processes produce the most district heating and electricity, and the fluidized-bed gasification processes have the smallest production of district heating and a negative production of electricity.

The conclusion of the Swedish study by Per Tunå is that the results showed a clear advantage for both the indirect and fluidized-bed gasifier when comparing efficiency to the entrained-flow gasifier. The advantage is proposed to be a direct result of the methane output in the producer gas from the gasifier.

However, the study also revealed that the entrained-flow gasifier has an advantage when it comes to tars in the producer gas, as the other gasifiers have considerable amounts of tars under real conditions. This tar must be removed in the process, and even though tar removal may not affect the biomass-to-SNG efficiency it will increase plant operating and investment costs.

Choosing between the gas cleanup and upgrading systems, Tunå concludes that the simplest system - zinc oxide desulfurization and PSA gas cleanup coupled with either methanation system, is the best choice. The reason for the conclusion is that this system is based on well established, widely used equipment and it offers better efficiency than a wet gas cleanup such as Rectisol® (Tunå, 2008).

4 Bio-SNG cases – and parallels to Danish conditions

To integrate the technical potential of SNG production in a specific society context, it is decided to investigate different cases where SNG is proposed or used within heating, transportation, energy security or climate change mitigation.

4.1 Individual heating of houses in Holland

In Holland the consumption of natural gas represents 46 % of the (primary) energy consumption[12], with main applications in chemistry (7 %), power production (23 %), and the production of heat (70 %). Production of heat represents by far the largest consumption, and more than 40 % is consumed by households. The result of this is that aside from industry, essentially all heat (96 %) is produced from natural gas (Zwart, et al., 2006). This makes natural gas the single most important energy carrier in Holland.

The Dutch natural gas grid covers more than 11,000 km pipe of various sizes and a vast collection of different plants and equipment for compressing, blending, metering and regulating the different gas flows – making the grid the most dense natural gas network in the world. Immense investments have been made in the system throughout the years, and a recent peak - and subsequent decline in the domestic production/procurement of natural gas - makes it a hot topic to secure the usage and maintenance of the system in the future.

To address the future gas production deficiency and secure the energy supply for the Dutch community, the Government has initiated an Energy Transition Activity with five Platforms, with one of the platforms dedicated to new gas options. The "Platform New Gas" includes a defined ambition to replace 20 % of the natural gas by green gas by 2030, and 50 % before 2050. This corresponds to approximately 300 PJ in 2030 and 750 PJ in 2050 and by far exceeds the potential of (upgraded) biogas and landfill gas, which has been evaluated to a maximum of 60 PJ (Zwart, et al., 2006).This leaves a gap in the green gas supply of at least 240 PJ in 2030 and 690 PJ in 2050 – even if the country succeeds in utilizing all biogas and landfill gas.

In a feasibility study from 2006 by Zwart et al. from the Energy research Centre of the Netherlands (ECN), GasTerra and Gasunie a phased approach was suggested for implementation of Platform New Gas. The idea was to begin with a full utilization of upgraded biogas from anaerobic digestion of manure and agricultural wastes while preparing the technology platform and infrastructure for introduction of bio-SNG from domestic and imported biomass resources (Zwart, et al., 2006). The technology platform being developed by the ECN is well under way with the MILENA gasifier and the integration with gas conditioning and methanation as described in section 3.1.4, and the domestic knowledge on natural gas infrastructure could prove valuable in the integration process.

The first step of the process – green natural gas from bio-methane or upgraded biogas, is immediately approachable as the technology is readily available and it can be applied directly through commercial small-scale projects running on locally available resources. Typically, the biogas will be used directly for power production, mobility, or injection to a local low-pressure natural gas grid (Zwart, et al., 2006). The first

[12]The primary energy consumption in Holland was approximately 3,300 PJ in 2005

important step towards this green milestone was taken 5th of August 2010, where green methane from upgraded biogas entered the public gas grid for the first time. This small success is assumed to be the first step towards a 10 % goal of domestically produced green methane produced from upgraded biogas in the grid in the next 5-10 years (Gasunie, 2010).

Integration of large-scale bio-SNG from domestic and imported biomass resources is a lot more demanding due to both scale and level of technology. However, the study by Zwart, et al. finds that a 100 % substitution is possible due to the advanced gas infrastructure, the domestic knowledge on the subject and the progress in the development of suitable technology. The only limitation that is suggested in the study is the availability of biomass. It is the recommendation to inject the bio-SNG into the high- or medium-pressure sections of the national grid due to infrastructure and trade concerns (Zwart, et al., 2006).

On the subject of biomass availability, the study by Zwart, et al. finds that approximately 20 million tons of imported biomass will be needed every year to cover the 240 PJ of bio-SNG required to meet the 2030 goals of the Platform New Gas. This amount of biomass (mainly wood) corresponds to ± 4 % of the total current annual transhipment in Holland and less than the annual transhipment of coal in the Rotterdam harbour in 2006. Considering the existing practice and experience in Holland on shipment, and the international maritime infrastructure the targeted biomass import for SNG-production is assumed feasible. To strengthen the conclusion, Zwart, et al. suggests an approach that incorporates the following views on large scale biomass consumption for energy purposes (Zwart, et al., 2006):

- Transport costs can be significantly reduced when densification is performed, e.g. by producing wood pellets, pyrolysis-slurry, or pellets of torrefied wood.
- Investment costs for pre-treatment and densification are compensated by lower transport costs.
- Biomass pre-treatment by torrefaction has advantages with respect to allowing higher gasification efficiencies and cost reduction in intermediate storage, in addition to the transportation advantages.

It is also suggested to regard the possibility of other transportation options in relation to bio-SNG as energy carrier. As an alternative to domestic SNG-production, it could also be considered to convert the biomass to bio-SNG in the country of origin, and then transport the bio-SNG to Holland in the form of CNG (compressed natural gas), LNG (liquefied natural gas), or by pipeline. A more detailed study on the different ways to secure the resource for SNG production and the transport aspects is supposedly being carried out by the ECN (Zwart, et al., 2006).

In an economic assessment of various methods to heat homes in Holland from biomass conversion, van der Drift, et al. concludes that SNG burned in individual homes is by far the cheapest of the considered options. The assessment includes the following three scenarios, which are all fuelled on the same imported biomass (van der Drift, et al., 2005):

- Large-scale SNG-plants with gas grid and local heat production by SNG combustion in individual homes, combined with large-scale BIGCC power plants for electricity production (Biomass gasification Combined Cycle).
- Small-scale local combustion of biomass with district heating production and heat grid combined with large-scale BIGCC power plants for electricity production.

- Medium-scale Combined Heat and Power (CHP) plants with district heating grids.

The main assumptions of the investigation are summarized in Table 4-1.

Table 4-1: Main assumptions in economic evaluation of the heating of Dutch homes with biomass (van der Drift, et al., 2005)

	SNG plant	BIGCC	CHP	Local heat plant
Hours/year	8000	8000	4000	4000
Typical size ($MW_{th\_biomass}$)	500	500	20	5
Plant heat efficiency	70 %	-	40 %	90 %
Plant electricity efficiency	3 %	45 %	30 %	-
Loss in gas grid	1 %	1 %	1 %	1 %
Loss in electricity grid	4 %	4 %	4 %	4 %
Loss in heating grid	15 %	15 %	15 %	15 %

Furthermore, it is assumed in the assessment that 95 % of the energy in the SNG is converted to heat in the houses and that the annual cost of investment, operation and maintenance are assumed to be 20 % of the total investment. The cost related to the transportation of gas, biomass, heat and electricity is not included in the calculations.

The conclusion of the simple economic assessment is that heat from biomass can be produced cheaper via SNG than by the alternatives of combined heat and power or local combustion units. The result is assumed to arise from the large scale of the SNG plant combined with the possibility to run this plant the whole year and store the produced gas, in contradiction to the direct heat producing plant that runs mainly during the cold season (van der Drift, et al., 2005). Unfortunately, the Dutch study does not include energy balances and overall efficiency evaluations. The results are focused solely on economic benefit, and the many significant simplifications make it difficult to use the calculations to draw additional conclusions. Some of the potential benefits of SNG in Holland are summarized in Figure 4-1:

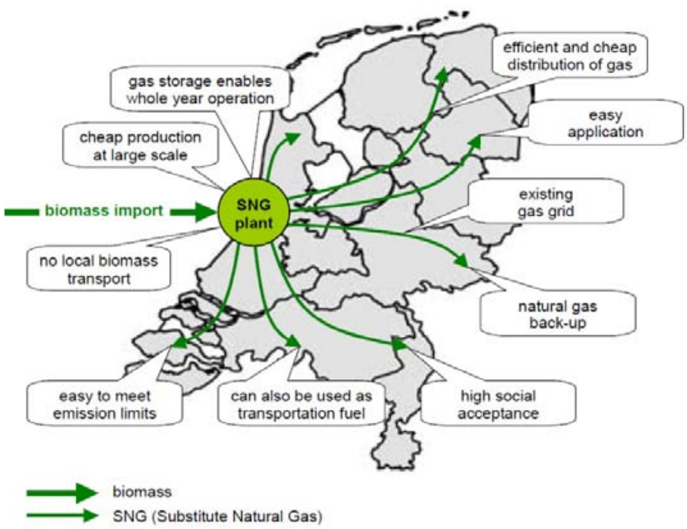

Figure 4-1: Potential benefits of producing SNG from imported biomass for the heating of Dutch homes (van der Drift, et al., 2005)

4.2 District heating in Sweden

The Swedish energy sector is a heterogeneous composition of fossil fuels, nuclear and renewable energy. The country has the highest share of renewable energy in the European Union – around 45 % in 2009, with additional political demands for an increase to min. 49 % in 2020. The highest share of renewable electricity is delivered by hydropower, amounting to 52 % of the total Swedish electricity production in 2007, but the largest renewable share of the total energy consumption is derived from the conversion of biomass – especially wood (SEA, 2009). Conversion of biomass accounted for around 32 % of total consumed energy in Sweden in 2009, and the growth in biomass use is significant. Projections show an increase from 2009 to 2010 of approximately 35 PJ, and the total potential for energy from biomass has been estimated to be as high as 40-55 % of the country's total consumption (corresponding to 600-800 PJ of a total consumption of 1500 PJ). Additional potential is expected primarily from forest thinning, waste wood, energy crops and peat (Karlsson, et al., 2005). Today, the share of energy from biomass in Sweden accounts for more of the total consumption than nuclear power and hydropower combined, and in 2008 biomass overtook oil as the single largest energy source in the Swedish energy sector (svebio.se, 2010).

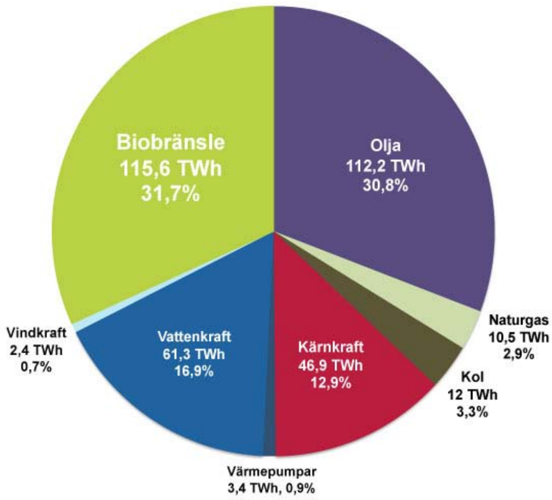

Figure 4-2: Overview of energy sources in the Swedish energy sector. Shares are calculated for 2010 by svebio.se, based on a short term prediction by the Swedish Energy Authorities. Purple share is oil, and the others are (in clockwise rotation): natural gas, coal, heating pumps, hydropower, wind power and biomass (svebio.se, 2010).

Due to the high impact and future potential of biomass in the Swedish energy sector, several studies have been made on optimal utilization of the resource. Two recent studies encompass SNG production in energy systems with widespread district heating. The results of these studies are described in more detail below.

4.2.1 Economic assessment of co-production of bio-SNG and district heating in Linköping

In a study from 2010, Kristina Difs et al. model a series of scenarios with different ways to improve the economy and emission level of the district heating system in Linköping in Sweden. Linköping is Sweden's 5th largest city with approximately 140,000 inhabitants. The district heating system is owned and governed by the municipality, and there is a yearly requirement for delivery of 1700 GWh of heat and steam with a max. load around 500 MW. The base load is delivered by waste incineration (Difs, et al., 2010).

The technology choices that are assumed available in the study include:

- The Güssing process, which is a biomass gasifier connected to a gas engine. The process involves gasification of wood chips in a dual-bed fluidized atmospheric gasifier, with steam as gasification agent, followed by cooling, cleaning and firing in a gas engine for CHP production. Efficiency of the plant is estimated as 20 % electricity and 52 % heat based on LHV of fuel.
- The Värnamo process, involving a biomass gasifier and a combined cycle. The power-to-heat ratio of this process is estimated to be considerably higher than in the process with the gas engine. Efficiency of the process is estimated as 43 % electricity and 47 % heat based on LHV of fuel.
- SNG production plant, where district heating is produced as a by-product in a bio-SNG production process. The plant involves gasification in a pressurized oxygen blown circulating fluidized-bed gasifier, followed by a high-temperature filter, catalytic tar reforming, water-gas shift and methanation. The process yields a small production of electricity, but the amount is not nearly enough to cover the process demands. Efficiency of this plant is estimated at -4 % electricity, 23 % heat and 69 % biomass-to-SNG based on LHV of fuel.

Choice of the different gasification technologies is compared to a reference with a conventional wood chips fired steam turbine CHP plant. This plant is assumed to have an efficiency of 30/81 for input capacity of 20-160 MW and 34/74 for input capacity 160-300 MW based on LHV of fuel.

Modelling is done in six scenarios using MIND (method for analysis of industrial energy systems), which is a tool built for optimization of dynamic energy systems. A long range of input is used as influential parameters in the scenarios to study the impact of various economic factors on the profitability and emission levels of the scenarios. Results are based on cost-optimization of investments, operations and the trading of heat, renewable electricity and biofuels.

The results of the study show that the introduction of gasification technology in the district heating system will prove to be a good investment in almost all cases compared to the reference with introduction of biomass CHP boilers. The scenarios show more cost-effective systems in all scenarios with introduction of gasification technology, and the choice of gasifiers instead of conventional CHP technology yields larger potential reductions of global CO_2 emissions. The work also concludes that the high value of bio-SNG could make the heat from a co-production of district heating and bio-SNG cost competitive even with heat from waste incineration, despite the fact that waste has a negative purchase cost (Difs, et al., 2010).

Even though the conclusions of the study may prove valid to some extent for Danish district heating systems, there is a profound difference to be acknowledged. Linköping is positioned in an area with an extreme richness of biomass – especially wood. This has a significant impact on both the economy and the emission levels of the procuring of fuel for the biomass gasification systems. Comparing the production of bio-SNG in such a biomass rich location with the general Danish conditions, where wood chip import is often the main biomass source, requires some interpretation. It may very well be beneficial to turn a domestic wood resource into bio-SNG to replace imported natural gas, even when there is a significant energy loss in the process. However, when the situation is turned upside down and bio-SNG from imported wood should replace domestically produced natural gas, it is no longer a certainty that the economic benefit holds true.

4.2.2 Economic evaluation of polygeneration of heat, power and transport fuels in Göteborg

In another similar study by E. Fahlén and E. O. Ahlgren from 2008-2009, the authors seek to assess *"the system consequences of integration of biomass gasification with an existing natural gas combined cycle heat and power plant, the Rya Natural Gas Combined Cycle CHP plant, in the municipal district heating system of Göteborg"*. In addition to evaluating the integration of biomass gasification with combined cycles for heat and power production, the study also evaluates the possibility for polygeneration of heat, power and transportation fuels (Fahlén, et al., 2009).

The study uses a model for district heating systems called the MARTES model combined with original calculations for the transportation fuel integration. As a prerequisite for the modelling, it is assumed that the production of heat should meet detailed heating demands at all hours based on 10 years of historical data, where, on the other hand, it is assumed that unlimited amounts of electricity and transportation fuels are demanded at all hours.

The economic assessment is supplemented with a robustness test that evaluates the different solutions on the parameter variation of mutually dependent parameters for electricity prices, fuel prices, CO_2 allowance prices (TEP), tradable green certificates (TGC), and Swedish fuel taxes for energy consumption and associated CO_2 emissions. The robustness test is done in six different scenarios based on 2006 settings in two of the scenarios, and future settings derived from a marginal-cost-based energy market model in the remaining four. The technological setups that are revised in the study are depicted below in Figure 4-3:

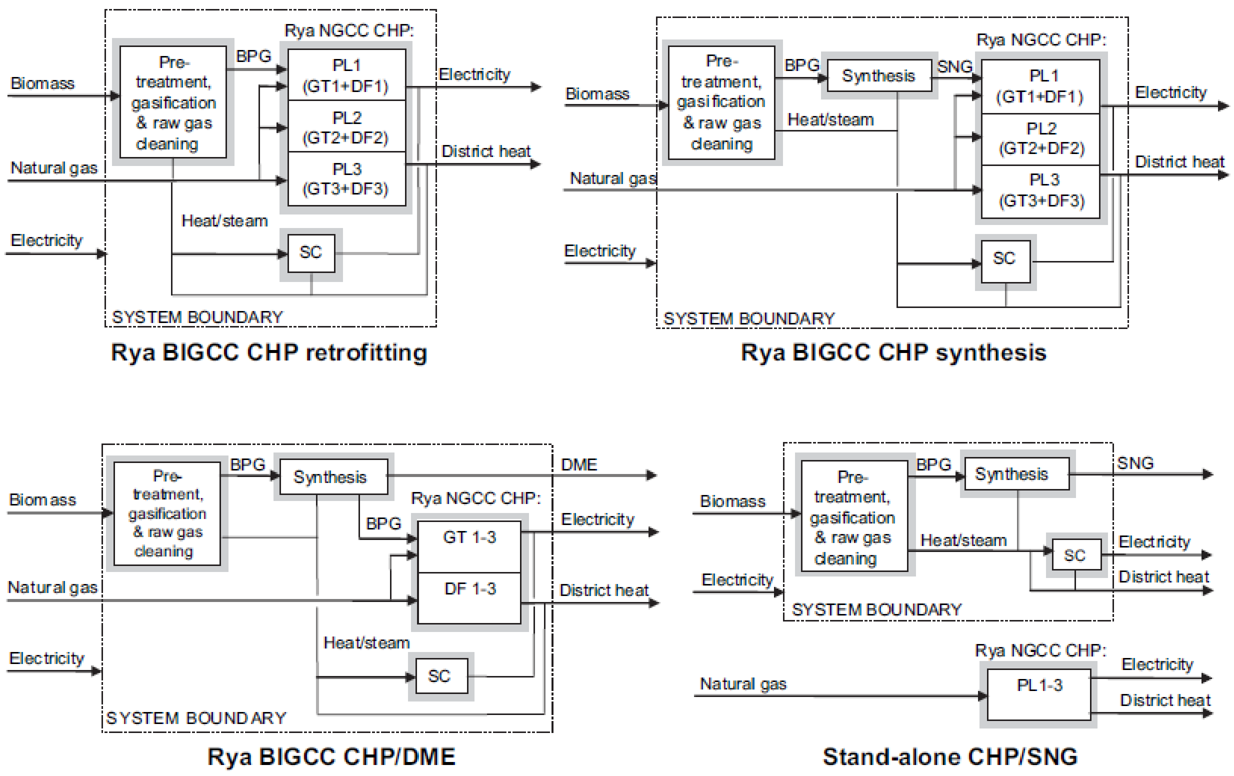

Figure 4-3: Technologically available options in the study by Fahlén and Ahlgren. BPG is Biomass Producer Gas, PL 1-3 is three available production lines in the Rya Natural Gas Combined Cycle CHP plant (Rya NGCC CHP), GT is Gas Turbines, DF is Duct Fired gas, SC is steam Cycle. Figure is from (Fahlén, et al., 2009).

The reference plant – the newly constructed Rya Natural Gas Combined Cycle CHP plant - has a capacity of 600 MW_{fuel}, and can deliver 295 MW_{heat} and 264 $MW_{electricity}$ at full load. The SNG stand-alone process is assumed to have a -4 % electricity efficiency, a 24 % heat efficiency and a 72 % biomass-to-SNG efficiency. For additional values and assumptions see the reference (Fahlén, et al., 2009).

Results of the Göteborg study are somewhat similar to the results from the study made on district heating in Linköping. All options yield a lower CO_2 emission ratio than the reference, which is quite obvious as energy from renewable sources is introduced. There is a large variation on the economic assessment results in the six different scenarios due to variations of fuel prices and policy tools. Despite the inconsistency of the results in the different scenarios, the authors conclude that there are some trends in the results. The retrofitting of the Rya NGCC CHP with producer gas from biomass gasification shows profitability in most cases, where the use of biomass for integrated SNG-production and firing in the Rya NGCC shows no economic advantages in any scenario. The economic performance of the stand-alone SNG-polygeneration plant with district-heat delivery shows robustness for many different levels of fuel, electricity and policy tool prices. The pattern is the same for the DME production, where the results indicate that a stand-alone plant will obtain better economy than an integrated ditto (Fahlén, et al., 2009). This is based on the limited need for district heating, and the combination with plant operation hours per year.

The SNG as well as the DME is assumed to replace petrol in the transport sector, giving these commodities relatively high value and good CO_2 balances. Sweden has come quite a long way in transportation on natural gas/SNG and biofuels, and, therefore, the concept is not utterly infeasible. In Denmark there are no incentives to drive on SNG, as there is not a single vehicle or filling station available, and, therefore, this way to utilize SNG from biomass is probably not possible in Danish scenarios in any near future. Combining this fact with the limitations on the Danish wood resource would probably reduce the economic incentives in combined SNG and district heating production found in the revised study when projected onto Danish conditions.

4.3 Additional experiences with SNG

Bio-SNG potential has also been investigated in several other countries that are not as similar to Denmark as Holland and Sweden. Some of these investigations are briefly presented in the following, as they contribute with new methodology, assessment details and perspectives.

4.3.1 Evaluation of bio-methane potential in Chile in 2006 and 2015

In 2009 the researchers Seiffert, Kaltschmitt and Miranda from the German Biomass Research Centre in Leipzig did an evaluation of the potential for bio-methane or green methane production in Chile. The investigation included methane from biogas as well as SNG from thermal gasification (Seiffert, et al., 2009).

The background for the study was the rapidly growing consumption of natural gas in Chile (78.5 PJ in the year 1990 to 327.6 PJ in 2005 – corresponding to 27 % of total energy consumption in 2005) and the correlated dependence on import from Argentina (around 68 % in 2006). The study focused on limiting the dependence on imported natural gas by substituting it with methane produced from domestic biomass resources. Greenhouse gas reductions and political climate goals were only regarded supplementary benefits.

The first task in the study was to evaluate the total biomass potential that could be converted to bio-methane. The main biomass resource in Chile is wood and forest residues, and the evaluation of this fraction of the biomass is highly detailed, and includes considerations on native forests, protected forests, plantations and wood industry. In addition to wood and forest residues, there is also a relatively small amount of straw, manure, energy crops and usable industrial wastes. The resource calculations were based on 2005 data, and the total potential was evaluated to be around 870 PJ, divided as indicated in Figure 4-4 below.

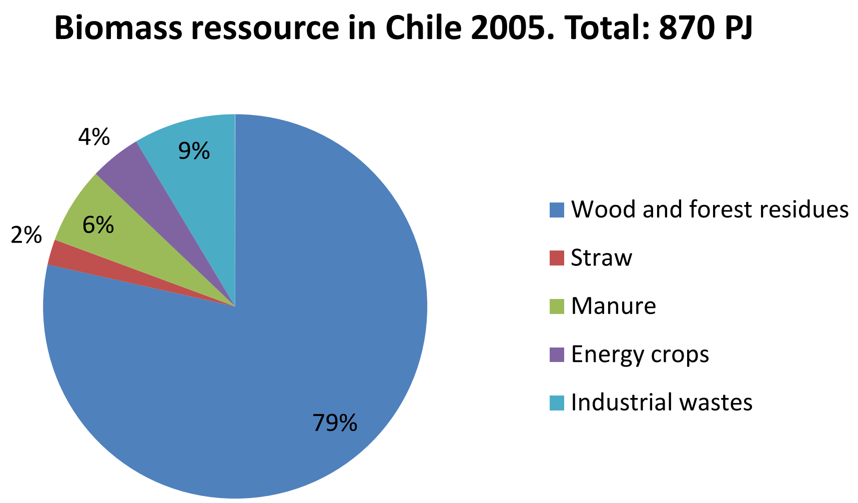

Figure 4-4: Biomass resource in Chile in 2005. Evaluated in (Seiffert, et al., 2009).

There are some important differences between Chile and Denmark to take into account at this point. Chile's geography is characterized by a very long area with many natural obstacles (mountains, rivers etc.) compared to Denmark, which is small and relatively compact due to an advanced bridge system. For this reason there are more remote areas in Chile, with little or no possibility to contribute to centralized biomass collection and energy production. One of the consequences of this is that it is only estimated as feasible to collect 25 % of the country's manure at most (Seiffert, et al., 2009). In comparison, the Danish Government has argued that it should be possible to use 50-75 % of Denmark's total manure quantity for energy purposes within 10-15 years (Fødevareministeriet, 2008; Klima-&Energiministeriet, 2010). Another important difference is that the food production in Chile is below 100 % of self-sufficiency, making it impossible to grow energy cops on other land types than fallow land. Denmark is self-sufficient on almost all categories of food production with capacities ranging from 70 % self-sufficiency on eggs as the lowest and 800-% self-sufficiency on pork as the highest (LF, 2009). On an overall basis Denmark is presently highly self-sufficient with food, and, therefore, it is considered more feasible to establish new areas with energy crop production in Denmark than in Chile.

To include the geographical challenges in Chile in the study on bio-methane potential, the authors have implemented catchment areas for resources for biogas production and bio-SNG production. This is based on an observation that the gas grid in Chile only covers selected sections of the long stretched country, and it is assumed unlikely that the large areas without grid connection could be able to contribute to the production of bio-methane. Catchment areas are set at < 25 km from gas grid for biogas (wet biomass) and < 150 km for bio-SNG (dry biomass) (Seiffert, et al., 2009). Similar limitations on an evaluation of Danish conditions would probably have only small impact due to a more widespread gas grid and more compact geography.

Bio-SNG potential is calculated with 65 % efficiency from biomass to SNG, and biogas potential is calculated with 55-100 Nm^3 gas/t agricultural residues and 350-500 Nm^3 gas/t manure with methane contents varying from 56-60 %. The total calculation on biomass resource, catchment area and conversion efficiency leads to an estimated bio-methane potential in 2006 values of 212 PJ/year with 94 % coming from wood and forest residues and only 6 % from manure, agricultural residues and energy crops (Seiffert, et al., 2009).

The study on Chile also includes two different scenarios for 2015 evaluation of bio-methane potential. In one scenario the gas grid is maintained as it is, and there is made no significant effort to increase the use of biomass for bio-methane production. In the other scenario an extra 1000 km of gas pipes are constructed and biomass utilization for bio-methane production is increased significantly. The main differences in the two scenarios are shown in Table 4-2 below:

Table 4-2: Highlights of the 2015 scenario settings for bio-methane potential in Chile (Seiffert, et al., 2009)

Change towards 2015	Scenario 1	Scenario 2
Extra gas grid constructed	0 km	1000 km
Expansion of plantation area	+1% per year	+4% per year
Increase in biomass production	+1% per year	+3% per year
Growth in wood industry	+2% per year	+8% per year

Implementations of the scenario settings above lead to 2015 bio-methane estimations of 232 PJ in scenario 1 and 429 PJ in scenario 2. This corresponds to 45 % and 84 %, respectively of the projected natural gas consumption in Chile in 2015 (510 PJ) (Seiffert, et al., 2009). The difference emphasizes the effect of increasing the catchment area in the case of Chile, and illustrates some of the practical differences between biomass resource assessments and practical collection and conversion potential.

4.3.2 Evaluation of present bio-SNG potential in Canada

Another country highly dependent on natural gas is Canada. Canada relies on domestic and U.S. natural gas resources, and as demand increases and a domestic gas production peak is expected in 2011, substantial efforts are now taken to evaluate potential substitutes. Bio-SNG as a potential substitute is assessed in a study from 2010 by Hacatoglu, McLellan and Layzell from School of Environmental Studies and Department of Chemical Engineering on Queen's University in Kingston and Institute for Sustainable Energy, Environment and Economy on University of Calgary. The study evaluates Energy Return on Energy Invested (EROI), economy, climate/greenhouse gas benefits and job potential in addition to quantifying the bio-SNG potential (Hacatoglu, et al., 2010).

The study is done with a reference scenario and an optimistic scenario based on data from 2004-2007. The evaluation does not include biogas from anaerobic digestion of wet biomass, but focuses solely on thermal gasification for production of methane and upgrading to bio-SNG. For energy and mass balance calculations it is assumed that the only available technology is pressurized oxygen-blown gasifiers followed by adiabatic methanation with intermediate cooling and upgrading through gas cleaning and CO_2 removal. According to the study this setup would have a biomass-to-SNG efficiency of 55 % in the base case, and 65 % in the optimistic scenario.

As it was the case with the study from Chile, the Canadian assessment also includes catchment areas for biomass collection. It is thus assumed that all biomass used for SNG-production must be collected within 50 km from the natural gas pipelines in the base case, and within 100 km in the optimistic scenario. The available land is divided into forest, good agricultural land and marginal soils with different production characteristics.

It is assumed that all biomass is dried to 15 % water before storage and SNG-production, and that excess process heat is used in the drying process and for electricity production.

The study also includes life cycle assessment with influence from the use of natural gas, diesel and electricity that is consumed in fertilizer production, agricultural operations and pre-processing of biomass resources prior to SNG-production.

Some highlights from the method are shown in Table 4-3 below to illuminate the difference between the base case and the optimistic scenario. For more details on the method, assumptions and specific values see the reference (Hacatoglu, et al., 2010).

Table 4-3: Selected highlights from Canadian bio-SNG potential analysis (Hacatoglu, et al., 2010).

	Base case	**Optimistic scenario**
Catchment area	50 km from grid	100 km from grid
Decline in industrial tree use due to closings of pulp and paper mills	0%	20%
Residue collection in forests (residue = 30% of wood production)	70%	80%
Wood production in forests	120 t dm/ha	140 t dm/ha
Residue collection from agriculture	50%	50%
Residue production in agriculture	1.0 t dm/ha	1.5 t dm/ha
Energy crops on marginal land	10%	15%
Energy crop production on marginal land	8 t dm/ha	10 t dm/ha
Energy crops on pasture land	20%	30%
Energy crops on crop land	3%	5%
Energy crop production on pasture land and crop land	10 t dm/ha	14 t dm/ha
Biomass collection from energy crops	80%	85%
Biomass-to-SNG efficiency	55%	65%
Process heat recovered for drying	70%	80%
Efficiency of electricity production	25%	30%
Reduction of process input energy due to technological improvements	0%	15%

The main result of the study is that production of bio-SNG from domestic biomass resources can substitute

16 % of the natural gas use in 2004 in the base case, and 63 % in the optimistic case. In addition to this, it is also investigated how the different steps in the process – the production of biomass, the transportation of the biomass and the conversion to bio-SNG influence the overall GreenHouse Gas (GHG) intensity, the cost of the bio-SNG, and the Energy Return On energy Investment (EROI) of the complete process. These results are shown in Figure 4-5 below. EROI values are unitless and indicate how many units of energy the process output provides in relation to the input of 1 equivalent unit of energy into the process. To compare, it is estimated that corn-based ethanol produced in the U.S has an EROI value of 0.8-1.6 and that synthetic crude oil extracted from Canadian tar sands has an EROI value close to 5 (Farrell, et al., 2006; Homer-Dixon, 2003).

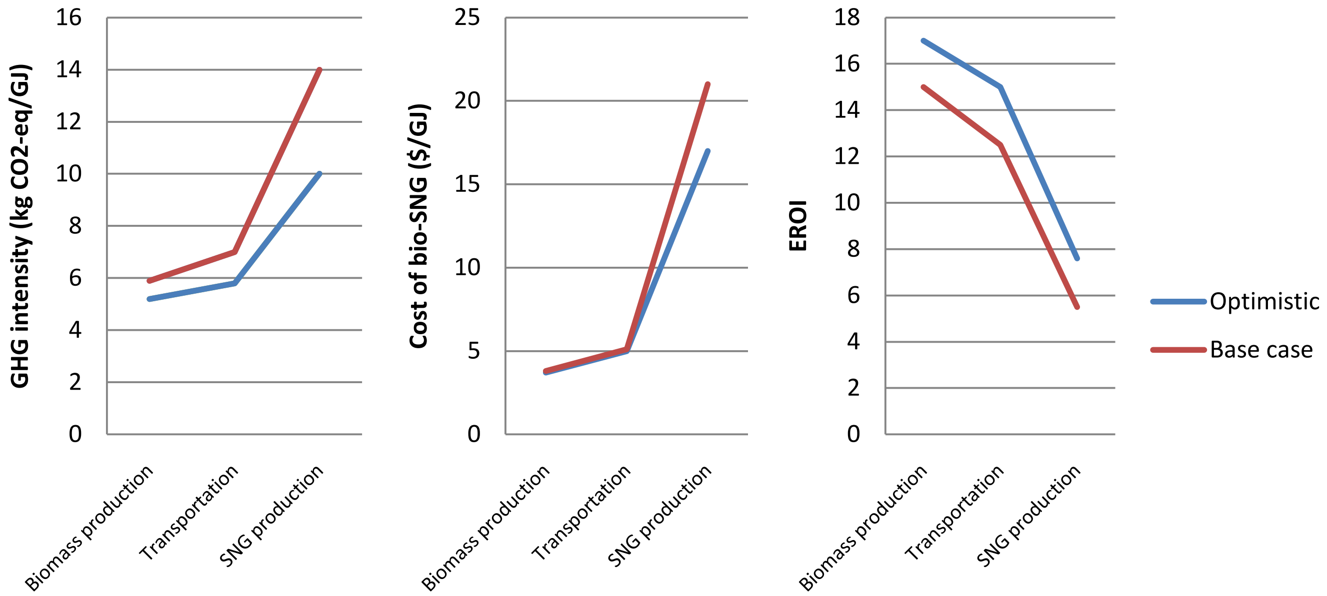

Figure 4-5: Process step impact in Canadian bio-SNG production on overall GHG emissions, cost and EROI (Hacatoglu, et al., 2010)

The results in Figure 4-5 are calculated as average value from production systems with capacities ranging from 500-5000 ton (dry) biomass harvested per day. The impact of scale is mostly on the transportation and cost factors. Detailed results show that EROI drops from 5.8 to 5.1 for the base case and 8 to 7.2 for the optimistic scenario when the process is scaled from 500 to 5000 ton (dry) biomass harvested per day. The GHG intensity is increased around 10 %, and the process costs are reduced almost 20 % when scaling the process up (Hacatoglu, et al., 2010).

The study does not go into detail on the optimal uses of the bio-SNG produced, but predicts that the climate impact of electricity production based on bio-SNG would be 8-11 % of the impact from coal based electricity production. It is not calculated what the impact of electricity produced directly on the biomass would be compared to the coal scenario.

5 The biomass potential in Denmark – now and the near future

Having addressed some of the aspects of SNG production – technology, infrastructure, experience and key stakeholders, the potential amount of available biomass will now be evaluated.

5.1 Design, construction and test of the biomass potential calculator

The present model seeks to estimate near-future biomass potentials (year 2020) based on a present day reference and a series of easy-to-use scenario parameters. Investigating data from recent years it was decided to use 2007 as representation of present day conditions as the dataset for this year is most complete and there was a possibility to compare model results to another similar investigation (Jørgensen, et al., 2008). The calculation model is built as illustrated in Figure 5-1. The illustration is significantly simplified, and, therefore, a detailed description of both the design and the construction follows below. All relevant parameters used in the model and scenario building are given in Appendix 1.

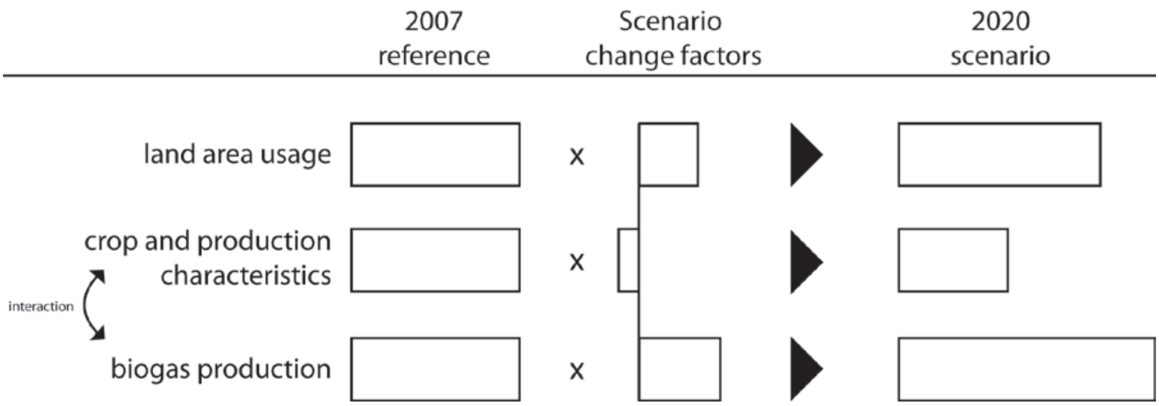

Figure 5-1: Simplified, overall design of the biomass potential calculator – example for illustration only

5.1.1 Land area specifications and usage 2007

First step in the biomass potential evaluation is an allocation of the total Danish land area available for biomass production/collection and other agriculture. Data for the 2007 reference is mainly from Blume, et al. from 2008 with reference to Denmark's Statistical Bureau 2007 and 2008.

The total area is divided into farm crop soil with 18 crop species in 5 categories. In addition, there is a section of land taken out of rotation/production. This area is divided into recovering areas (fallow fields) and protected areas (P-3 areas). The protected areas are furthermore divided into land requiring maintenance in the form of hay/grass collection or animal grassing and untouched (and thus non-producing) areas. Data for the subdivision of the P-3 area is from (Buttenschøn, 2007). The fallow field area is also subdivided - into areas with grass, areas with energy crops and non-producing areas based on data from Jørgensen, et al (2008).

In addition to farm soil areas there are also main forest areas and minor forests/gardens/parks. The main forests are divided into different tree types, supplement areas and temporarily uncovered forest areas. The last two categories are assumed to give no yield. Data used for the allocation of the different forest type land areas is from Denmark's Statistical Bureau from 2000, and applied to the total forest size of 2007. Minor forests, gardens, parks etc. are not area determined but simply estimated to yield 10 PJ of biomass in 2007 (Klima-&Energiministeriet, 2010).

5.1.2 Crop and production characteristics 2007

Having determined the different areas for biomass production in Denmark, 2007 the next step is to apply some biomass and production characteristics. These characteristics provide an estimation of total crop production energy input and output energy in the biomass, which are essential factors in assessing the combined net potential. Crop energy output calculations include crop water content, crop yield (main crop and crop residue), and energy content as lower heating value (LHV). Production input includes fertilizer production and use, watering, diesel consumption, pesticides, machine construction etc.

Most data has been recalculated to give average values for a combination of main Danish soil types. Original data is from a more detailed study by Blume, et al. from 2008 combined with specific values from a suitable online lexicon (Force_Technology, 2010). In addition, this section is supplemented with information on clover and energy grass (Jørgensen, et al., 2008), alfalfa (Boateng, et al., 2006), willow (Fødevareministeriet, 2008; Larsen, 2008), forest yields from 2000-2008 (Denmark's Statistical Bureau, 2009), different tree types (Energistyrelsen, 1996) and hemp (Pallesen, 2008).

During the construction of this section of the model, some important assumptions have been made. These include:

- Differences in yield from willow on farm soils and marginal soils are transferred to energy grass and hemp as well.
- Forest operations and permanent grass production are assumed to have the same energy requirements as the mechanical operations of production of grass on farm soil.
- Energy input in crop residues is allocated by weight, meaning that the energy required to produce the residue is assumed to be:

$$energy\ input\ residue = \frac{weight\ residue}{weight\ total\ crop} \cdot energy\ input\ total\ crop$$

- No distinction is made between conventional farming and ecological farming, and, therefore, the values used for the reference scenario represent a farming system with the same share of ecological farmers as was present in Denmark 2007.

5.1.3 Animal quantity, animal straw usage and manure production 2007

Production of milk, meat and other animal products has an enormous impact on Danish agriculture. In 2007 around 73 % of the total arable land area was used for fodder production. In addition to grain and other primary crops, the large amount of farm animals in Denmark also consumes much of the plant residues – like straw, for use as both fodder and maintenance (Blume, et al., 2008).

To include biogas in the evaluation, it is important to incorporate a correlation between the number of farm house animals (cows, pigs, horses, poultry), the amount of straw used for these animals and the manure production. In the present model this is done with the following assumptions:

- All animals are re-calculated into pig-equivalents with cattle = 1.5 PE, sheep = 0.5 PE and all poultry and small animals = 0.2 PE. Total number of PE is calculated from data by Denmark's Statistical Bureau from 2008.
- Assessment of straw production and straw usage is based on average values from 2006-2008 from Denmark's Statistical Bureau. Data includes production, collection, use in animal production and use for energy purposes. From this, a reference value for straw use per PE is calculated, which is improved through comparison with (Jørgensen, et al., 2008).
- It is assumed that a maximum of 83 % straw (dry matter) can be collected from the fields (Gylling, et al., 2001).
- Manure production per PE is calculated as an average from several different types of pigs and livestock (Miljøstyrelsen, 2007).
- Dry matter content in Danish average manure is for PE manure production (Jørgensen, et al., 2004).
- Ash fraction is immense (20 %+) and is subtracted to give energy content in organic fraction of average Danish manure (Sommer, et al., 2010)
- Average methane production from anaerobic digestion of average Danish manure and ensilaged grass under typical Danish conditions can be used in the calculations (Jørgensen, et al., 2008).
- There is assumed no benefit or penalty in biogas production from mixing different ratios of manure and grass.
- Energy-input in manure is neglected as insignificant. Instead energy input is assumed to be in animal fodder and straw production.

5.1.4 Biomass reference calculations – 2007 assessment

To test the quality of the reference calculations, and to illustrate some of the factors that have not been mentioned in the previous three sections, a comparison is made between the present biomass potential calculator (reference 2007), and a well acknowledged equivalent (Jørgensen, et al., 2008). The following parameters are incorporated in the calculations to have similar origins of reference:

- 65 % (wt) of straw from grain production is collected
- 14 % (wt) of straw from rape production is collected
- 4 % (wt) of total manure production is used for biogas production
- Fibre fraction from biogas production is used as fertilizer
- No grass is collected on P-3 areas for energy purposes

These settings give a very fine agreement between the two calculations, which is illustrated in the two right hand columns in Table 5-1:

Table 5-1: Comparison between calculations of bio-energy potential 2007 from (Jørgensen, et al., 2008) and the present model

	Jørgensen (2008) LHV (PJ)	Present model LHV (PJ)	Difference PJ	Difference of total %
Energy crops	0,5	0,5	0,1	0,2
Straw from grains	18,5	19,5	1,0	2,2
Straw from rape	0,7	0,5	0,2	0,4
Forests, gardens and parks	25,4	25,4	0	0
Biogas from manure	1,1	1,0	0,1	0,2
Total energy potential	46,2	47	0,8	1,8

It was a prerequisite for the agreement between the two calculators that the average straw consumption per PE was changed from 123 kg/PE·year to 133 kg/PE·year in the developed model. The calculations on animal hold and straw consumption are much more detailed in (Jørgensen, et al., 2008), and, therefore, it seemed reasonable to adapt the improved value. Without the enhancement the difference in straw from corn would be 6.9 % and the difference in total potential 6.3 %.

5.2 Description of parameters for scenario-building

Building scenarios in the developed model means to influence some of the reference values on crop application, forest growth/decline and improved production techniques, etc. The parameters that can be used in this way are described in the following.

5.2.1 Year of assessment

First parameter to set is the year of the potential calculation. This has influence on the forest area due to political ambitions about doubling the Danish forests in one forest generation (80-100 years) (Blume, et al., 2008). Today the forest area is around 14 %, and to meet the criteria of the political desire then it must grow by around 5000 ha every year. The specific growth rate can be altered from scenario to scenario.

The forest expansion takes up land from the unused farm land. If there is no unused farm land left, then crop soil has to be used instead. It is assumed that cities, roads etc. do not grow or shrink significantly in size within the time frame of the calculations.

5.2.2 Allocation of land

Having set the year of assessment, and thus deducted the forest expansion, the next step is to allocate the crops of the desired farming systems on the available farmland. This is done by adding or subtracting hectares from the allocation in 2007. Willow, energy grass and hemp was allocated 0 ha in 2007 and, therefore, they must be prioritized to produce any of these crops.

Political demands on protected areas (P-3) also play a role in the allocation, and farming at the expense of these areas is not plausible. Today restrictions exist on both national and EU level. It is, however, possible to harvest energy crops with reduced yield on some marginal soils and grass as part of P-3 maintenance on a selectable percentage of the land.

When more farm soil is allocated in the scenario than in the reference, this new land is first subtracted from marginal farm soils and fallow fields left unproductive for recovery. If no more of this land is available the area is deducted from the protected areas. Sometimes restrictions on P-3 areas or non-productive areas will force the scenario to reduce the amount of farmland in rotation instead.

5.2.3 Quantity of animals, and consumption of straw per PE

The large number of animals in Danish agriculture uses a lot of the produced straw and claims a lot of the arable land for fodder production. Therefore it is important to be able to change the number of animals when building specific scenarios. In the present model, this is done by adding or subtracting "% Pig Equivalents" from the 2007 reference quantity.

It is also relevant to change the amount of straw used per year per PE. This relates to the production standard of the produced animals and is expected to go up in sustainable eco-friendly scenarios, while it would probably go down in a market-based, restriction-deprived scenario.

Final parameters to alter in this part of the scenario setup are the percentages (weight) of straw collected for the different crops. Maximum collection is recommended to be 85 % (Gylling, et al., 2001) or even 88 % (Olesen, 2009).

From these parameters the available amount of straw for energy/fertilizer purposes is calculated alongside the total amount of collected straw and the straw used for animals. In addition, it is calculated how much manure can be expected from the specified scenario.

There is no built-in correlation between the amount of animals in a scenario and the fodder production. Therefore, it is important to be aware of the need for fodder when changing the quantity of animals or fodder producing fields. In 2007, 73 % of the arable Danish land was used for fodder production, and there was a simultaneous import of $1.8 \cdot 10^9$ kg soya beans for use to feed animals. On top of this a range of waste streams from agriculture is also used for this purpose, so the amount of fodder required is enormous and the complexity of these calculations exceeds the purpose of the present model.

It is possible to redirect classic fodder crops like alfalfa, corn residue or clover grass from animal feed to energy purposes. The mentioned crops all have some unique advantages in energy production, and the only reason they are used elsewhere is the huge food requirement for animal production (Blume, et al., 2008).

5.2.4 Production of biogas

As biogas plays a significant role in the Government's energy visions (Klima-&Energiministeriet, 2010), and also has the potential to contribute to SNG production as bio-methane or green methane it is an important part of the potential evaluations. In the developed model, the biogas output is altered by deciding how much manure, grass from P-3 areas, grass from non-producing farmland and residues from beet production should be allocated to biogas plants. In 2007 only 4 % of the manure was digested in biogas plants, but it is the goal of the present Danish Government to increase this amount to 50-75 % within the next 10-15 years (Fødevareministeriet, 2008; Klima-&Energiministeriet, 2010).

5.2.5 Collection of biomass and overall change parameters

To make it as easy as possible to test scenarios with simple overall alterations, a series of parameters for this purpose is incorporated in the model. The first parameter defines how much of each crop or crop residue is collected from the fields, and how much is utilized in energy production. This parameter could be used to easily introduce the effect of sustainability requirements or improved agricultural machinery in the scenario.

The second set of overall parameters can influence the crop yield for specific crops compared to 100 % in 2007. In this way it is very simple to introduce reduced crop yields from climate change effects as well as improved crop yields from advancements in growing operations or GMO[13] crops.

The final set of parameters allows for a simple adjustment of the energy input per ha in the production of each crop. Combined with the previous set of parameters, this could be used to implement a simulated effect of increased ecological farming, soil layer depletion or improved soil quality from restoration initiatives or biochar amendment.

5.3 Evaluation of the Danish biomass potential in three 2020 scenarios

It is predicted by the Danish Government in the annual energy outlook from 2010 that the total energy requirement for Denmark in 2020 will be approximately 846 PJ. Of these 846 PJ it is a specified political goal/commitment to reach 30 % sustainable energy. This would add up to a total amount of 254 PJ including the less sustainable energy in biodegradable waste and import of biomass from unsustainable growth (Energistyrelsen, 2010).

Based on the present wind power capacity being projected before 2020, the legislation on combustion of waste and other influential factors the outlook from 2010 predicts a production from wind power, bio-degradable waste and “other sources”[14] of approximately 85 PJ in 2020. Use of waste in energy production was approximately 25 PJ in 2009-10 and no more energy is expected from this source in the present study. If import of unsustainably produced wood from America, the Baltics etc. is stopped, that would leave a gap of approximately 145 PJ biomass in order to reach the goals of 30 % sustainable energy in 2020.

Three different cases are presented below that will try to achieve 30 % sustainable energy in 2020 under influence of various factors. The scenarios are focused only on the contribution to the energy by agriculture and forest management. Wind power and “other sources” are assumed to deliver as projected by the Danish Government in the energy outlook. Based on this, the scenarios are matched against their ability to provide 145 PJ of energy in the form of ready-to-process biomass (liquid/solid) or biofuel of various types

[13] Gene Manipulated Organisms
[14] “Other sources” Includes solar power, solar heat, geothermic heat, hydro power etc.

(bio-oil, SNG, ethanol etc.), which can all be converted to electricity and/or heat and transported to the end consumer with efficiencies comparable to 2010 averages. The included scenarios are:

- A political scenario built on the ambition to maintain business-as-usual in agriculture, but comply with 2020 goals. The main internal changes are the utilization of farm soil for energy crop production and increased utilization of straw, manure and residues for energy purposes.
- A climate change scenario based on predictions about climate change impact on farming conditions in Denmark. Variations in crop yields, changes in the selection of suitable species for more robust business and production setups, and an increase in the use of pesticides and herbicides are main influential factors in this scenario.
- A scenario thriving for a more environmentally concerned and sustainable agricultural management. In this scenario some of the harmful long term effects of modern agricultural management are mitigated with structural changes in land use, increased biodiversity and decreased animal production. Climate change effects are not included in this scenario.

5.3.1 Energy Return On energy Investment

In all scenarios the input energy in the production of the biomass is included – including the cost of procuring that energy. However, the continuous changes in the energy requirements on the procuring of e.g. diesel oil should also be included to give a reasonable estimate of the input/output relationship in the different 2020 scenarios. These changes are known as changes in the EROI - Energy Return On energy Investment – a factor describing the energy yield from a specified energy production operation depending on the input (Hall, et al., 2005).

Predictions on the development in e.g. diesel oil EROI are very dependent on the specific situation, and even in the small span from 2007 to 2020 it is very difficult to give precise predictions. This is especially true for Danish conditions as the domestic focus on the matter has been limited, and no thorough investigation is available. The change in diesel oil EROI over the short period from 2007 to 2020 could prove to be limited, but it is more likely to have a significant impact. Based on a highly simplified trend line from 1930 (EROI 100[15]) over 1970 (EROI 25) to the 1990's (EROI 10-18) the EROI of oil in the United States would shift from around 9 in 2007 to 6 in 2020 and turn 1 somewhere around 2075 (estimated with data from Hall, et al. (2005) and Cleveland (2005)). The prediction is not applicable under Danish conditions, and is based on too little data in any case. However, it is probably relatively safe to predict a strong decline in diesel oil EROI as a function of time, as finding new oil today may have EROI values close to 3, while alternatives like oil production from Canadian tar sands have EROI values as low as 1.1 or 1.05 and biobased alternatives like ethanol could prove to have negative energy returns under most conditions (King, 2007; Murphy, et al., 2010; Cleveland, 2005).

The large historical shifts up and down over relatively short periods make it impossible to include any factorial estimation in the present work, and it is chosen to exclude the factor with a comment that the energy input in the predicted production will most likely be strongly underestimated!

[15]An EROI of 100 in diesel oil production would imply that 100 barrels of oil could be delivered to consumers for every 1 barrel invested in the procuring/production.

5.3.2 Effect on biomass potential 2020 forced by political bio-energy requirements

The first scenario is largely built on a report by Uffe Jørgensen, et al. from 2008 supplemented with recommendations by Gunner Boye Olesen in a report from 2009.

As part of the first scenario, it is expected that increasing prices on straw will lead to a decrease in animal production, and an increase in straw production for energy purposes. The adjacent change in farmers' mindset could lead to new choices of cereal crop or crop sorts to increase straw production. The assumption is based on the fact that in recent years straw prices have approached grain prices rapidly, and in March 2009 straw prices topped at 75 DKK/100 kg with a simultaneous price on grain at 82 DKK/kg for oat and 92 DKK/kg for wheat (Kjærsgaard, 2009; statistikbanken, 2010).

An example on straw yield variations from choice of species and yearly differences is shown in Figure 5-2.

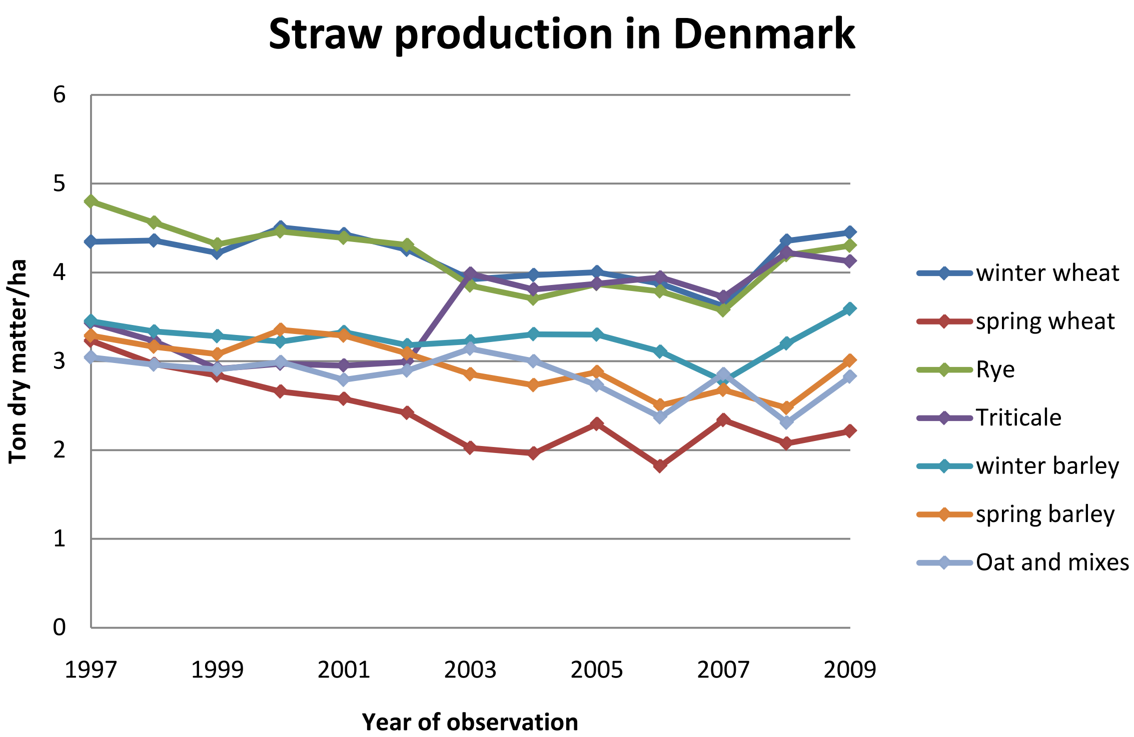

Figure 5-2: Straw production in Denmark from 1997 to 2009 (statistikbanken_b, 2010)

The data in Figure 5-2 very clearly show that there are large differences in straw yields depending on choice of species and year of production. For many years, the development of cereal crops has been going from more to less straw, but with the present focus on biomass for energy purposes, it is assumed possible to reverse this trend and optimize cereal production to include high straw yields.

The primary settings of the scenario are as follows (Jørgensen, et al., 2008; Olesen, 2009; Hall, et al., 2005):

- 50 % of all high fallow fields is used for energy crop production (willow or miscanthus grass).
- Protected areas (P-3 areas) are not used for energy production. The area is similar to 2008.

- 75 % of all low areas not suitable for intensive agriculture is used for production of grass for biogas.
- 15 % of the present area for production of cereals is converted to energy crops.
- 15 % fewer produced animals (pig equivalents).
- 80 % of the straw that is not used for animal production is used for energy purposes. This includes straw from cereal production and seed production and sums up to a total straw material collection from the fields of 86 % weight.
- It is assumed that an additional +10 % weight is produced in straw from winter wheat as a consequence of higher prices on straw, sort improvements and priority. This is assumed feasible as straw yield has been deliberately decreased by at least 25 % weight over the last century. Assumption is based on (Larsen, et al., 2009; Larsen, et al., 2010).
- No seed oil used for energy purposes.
- Additional 50 % of wood and forest residues is collected from large forests (Skoven, 2010).
- The forest area is the same as in 2008.
- The yield from gardens, parks and small forests is the same as in 2008.
- 75 % of the total amount of manure produced by farm animals is used in biogas production.
- Fibre fraction from biogas production is collected for energy purposes.

These settings give the following biomass dry matter yield in the model established in chapter 5.1.

Table 5-2: Energy potential of biomass produced and collected in 2020 scenario with business-as-usual approach to fulfilling the EU requirements of 30 % sustainable energy

	Output	**Output**	**Input**
	Megaton dry matter	PJ energy in available biomass (LHV)	PJ energy in diesel, natural gas etc.
Energy Crops	3.2	51.3	2.8
Straw from cereals	1.9	33.3	6.9
Straw from seed production	0.3	4.7	1.4
Wood and forest residues	1.7	33.1	1.2
Grass and clover grass	0.3	4.2	0.1
Manure	1.5	20.2	-
Total	8.8	146.8	12.4
Net output	-	134	

This concludes the assessment of the biomass energy potential in a 2020 scenario, where only slight structural changes are made, and business-as-usual is preserved as much as possible.

The net output of the biomass production is approximately 134 PJ. This does not quite meet the requirements of 145 PJ to match the 2020 EU goals on 30 % sustainable energy. However, there is still a potential extra gain in the development and application of improved/more suitable technology for converting the biomass energy potential to electricity, heat and transportation energy. An increase in the average efficiency in the Danish energy sector would decrease the future demand for biomass.

5.3.3 Effect on biomass potential 2020 forced by climate changes

The global climate is changing, and predictions for impact in Denmark show a qualitative agreement that average temperature will increase, precipitation will increase in autumn/winter and decrease in summer, and seasonal deviations as well as year-to-year deviations will be more significant in the coming years. This will result in more drought seasons, more extreme rain periods and less frost during winter (Olesen, et al., 2006). Despite the agreement in the nature of the coming changes, there are some significant differences in the quantification of the matter. Olesen (2006) estimates a 3-5 °C temperature increase on yearly average, with 20-40 % more rain during winter, 10-25 % less rain during summer and a rise in sea level of around 25-50 cm in the year 2100. Other estimations are more severe and some neglect the influence completely. The point of the present report is not to discuss the quantitative impact of human behaviour on our climate, but to try to quantify the impact of the climate on agriculture and the production of biomass through a qualitative analysis of climate change effects and agriculture adaption techniques. Therefore, some of the initiatives included in the scenario will probably be exaggerated and others understated compared to what will prove necessary in real 2020 conditions. Some of the influential factors that have to be addressed in the scenario are (Olesen, 2005; Olesen, et al., 2006; Schelde, et al., 2009):

- Higher temperatures lead to longer growing periods for crops that do not ripen (e.g. beets or grass), and shorter growing periods for crops that do ripen (e.g. cereals). The following decrease in yield from crops that ripen is most significant in winter crops and less significant in spring crops.
- 1 °C average temperature increase in Denmark will assumedly lead to a 1 month longer growing season (with “growing season” defined as average temperature >+5 °C).
- Corn/Maize will probably benefit from the extended growing season, even though it ripens as it usually still grows into the autumn months.
- Rising sea levels will flood some low positioned areas, decreasing the total area for agriculture and making the adjacent areas more susceptible to pollution from pesticides and leaching of nutrients.
- Increased CO_2 levels in the atmosphere may improve the growth of most crop types. Maize/corn with C-4 photosynthesis will not benefit as much from an increase in CO_2 concentrations as especially legumes and root crops will.
- Increased temperatures and precipitation will improve growth conditions for some species and sorts, but at the same time make others more vulnerable and give large variations in yields from year to year.
- Increases in temperature and precipitation will also open up to large-scale production of species that have not been regarded as suitable in Danish climate up till now. Sunflower, soya beans and maybe grapes could prove compatible with Danish conditions in future scenarios.
- Weeds, pests and plant diseases (especially fungi) will have a larger impact on crop yields due to better weed/pest living conditions and higher crop vulnerability. Warmer winters with fewer frost periods will allow for increased amounts of harmful elements to survive from year to year.
- Soil fertility may be reduced as a function of increased microbial activity. Accelerated conversion of soil organic carbon will also release nitrogen compounds as nitrous oxide and probably increase nitrogen leaching as well.
- More heavy rain will lead to more nutrient leaching of especially nitrogen- and phosphorous compounds, and thereby increase the requirement for fertilizer and vulnerability of adjacent water systems.

- Increased crop yields as a consequence of higher temperatures and more rain will also require more fertilizer to maintain crop quality.
- A higher frequency in occurrences of drought and warm periods will increase the demand for watering.

As indicated there are both benefits and drawbacks to be expected in Danish agriculture as a consequence of climatic changes. In general, there will probably be higher crop yields in good years, but the increase in weather variations will pose many new threats and challenges at the same time. Fortunately, there are several ways to adapt to some of the impacts of climate change on agricultural systems. These include (Olesen, 2005; Olesen, et al., 2006; Schelde, et al., 2009):

- Cereal crop species and sorts can be improved or changed so systems produce more straw. Straw yield is less vulnerable than grain yield, and by focusing on both the farmers divide the risk. This opens for a stronger focus on triticale[16] as a combined food and energy crop.
- An increased number of different species and sorts can be introduced in rotation to increase the biodiversity of the agricultural systems. Highly diverse systems are less vulnerable to pests, climatic threats and diseases than homogeneous systems.
- To reduce the impact of shorter growing seasons on cereal production, it is an alternative to focus more on spring crops and less on winter crops. In combination with spring cereals it is feasible to plant clover grass beneath the cereals (under sowing). The clover will direct nitrogen from the air to the soil and will be ready to grow when the top crop is harvested. It is estimated that approximately 3 t dry matter/ha of clover grass can be harvested from such a production.
- To counteract the accelerated nutrient leaching and soil depletion consequences of a warmer climate with increased precipitation, it is essential to keep fields as “green” as possible for as long as possible. This mean that more perennial crops should be integrated in the agricultural management – like some grasses, willow/poplar, various herbs, fruits or nuts. Reintroducing the use of fallow fields could also aid in this process.
- Choosing grain sorts with longer growing periods and introducing earlier sowing of spring cereal and later sowing of winter cereal will help counteract the effect of temperature rise on cereal crop yield.
- Due to climate change mitigation strategies and energy concerns in the future, research in new sorts may shift from focus on high-quality products to a focus on high quantity products. As an example – sugar beet production in a more energy scarce society might stop improving sugar juice

[16]**Triticale** is a half-breed cereal crop created in a laboratory environment by crossing wheat with rye. The plant have a high phosphorous absorption rate, widespread root system, high straw production (+10-30 % weight compared to best wheat or barley), better yields than other cereals on marginal/sub-optimal soils (low nutrient levels, water shortage or rain variations) and it is overall relatively tolerant to cereal diseases. Triticale shows many of the benefits from both rye and wheat, resulting in a healthy, edible grain and high straw production in low input systems (National_Research_Council, 2002; Jolly, 2004).

quality and focus more on total sugar and biomass quantity. The knowledge about these sorts already exists, but is not used do to the fact that almost all sugar beets are processed for food applications.

From the list of climate change effects and adaption methods above, a set of parameters is set that defines the 2020 climate change scenario for biomass production. These parameters are given below.

- Winter wheat area, spring barley and winter barley area is reduced with 350000 ha, 250000 ha and 50000 ha, respectively.
- 150000 ha of additional spring wheat under sown with clover grass are added. It is assumed feasible to harvest approximately 2.5 t dry matter/ha clover grass.
- 100000 ha of additional spring triticale under sown with clover grass are added.
- 150000 ha of additional beets and root crops (especially sugar beets) are added.
- 50000 ha of corn/maize are added.
- 200000 ha of energy crops – willow and miscanthus grass, are added.
- 80 % of the straw that is not used for animal production is used for energy purposes. This includes straw from cereal production and seed production and sums up to a total straw material collection from the fields of 86 % weight.
- 25 % of residues from production of sugar beets and other root crops used for biogas production.
- Fibre fraction from biogas production is collected for energy purposes.
- Increased energy input in production from additional use of fertilizer, pesticides and watering: cereals (average 15 %), rape (15 %), corn/maize (15 %), beets and root crops (20 %), grasses (10 %), permanent grasses (0 %), energy crops (15 %).
- Additional yields from crops due to improvement of sorts and increases in temperature and CO_2 concentration: cereal straw (average 5 %), rape straw (5 %), corn/maize straw (10 %), beets and root crop tops (10 %), grasses (10 %), permanent grasses (5 %), and energy crops (5 %).
- 50 % of under sown clover grass collected for energy purposes.
- 25 % of straw from corn/maize production collected for energy purposes.
- All aspects of energy from forests, P-3 areas and fallow/outer areas and the amount of animals/manure for energy purposes are assumed to be similar to the previous scenario.

These settings give the following biomass dry matter yield in the model established in chapter 5.1:

Table 5-3: Energy potential of biomass produced and collected in a 2020 scenario integrating estimations of climate change impact and adaption techniques in Danish agriculture, and still aiming to fulfil the EU requirements of 30 % sustainable energy

	Output	**Output**	**Input**
	Megaton dry matter	PJ energy in available biomass (LHV)	PJ energy in diesel, natural gas etc.
Energy crops	2.8	46.2	2.9
Straw from cereals	1.3	22.6	6.5
Straw from seed production	0.2	4.2	1.7
Wood and forest residues	1.7	33.1	1.2

Grass and clover grass	2.0	22.3	1.8
Corn/maize straw	0.2	3.3	0.3
Root crop residues	0.1	1.2	0.1
Manure	1.5	20.2	-
Total	9.6	153.1	14.5
Net output	-	138.6	

The climate change scenario results suggest that the improved growth conditions from an increase of average temperature, CO_2 concentrations and precipitation may lead to slightly increased biomass yields. The gap between the political demand and the available biomass resource is only about 6 PJ in this scenario. However, the price of the additional production is a higher input of energy. The return of biomass energy (LHV) per MJ of energy invested in the two scenarios is ca 11.8 MJ biomass/MJ invested energy in the standard scenario and 14.5 MJ biomass/MJ invested energy. The climate change scenario is based on many assumptions and uncertainties. Impact from an increase in droughts, heavy rainfall, storms etc. is not included and is likely to decrease the biomass yield compared to the suggested amounts. New crop species could possibly be integrated to adapt to the changes.

5.3.4 Effect on biomass potential 2020 forced by a more sustainable agricultural management

In the last of the three 2020 scenarios, focus is on environment, sustainability and the achievement of the EU goal on 30 % sustainable energy. The primary influential factors in this scenario will be:

- A strong decrease in the number of animals produced in Denmark. A simplified calculation done by Henrik Hauggaard-Nielsen, agronomist and senior scientist at Risø DTU in Denmark, showed that if 9 kg animal fodder (dry weight) was required to produce 1 kg pig meat (dry weight), it would result in a consumption by the approximately 25 million fattened pigs in Denmark of ca 130 PJ fodder. Minimizing meat consumption and export will relief much of the strain on farm soil systems, and also free agricultural areas for energy production.
- The long-term cost of amending the externalities of certain types of agriculture may prove to be much higher than expected. Recent EU initiatives on the matter – like the Natura 2000 regulation and the water framework address some of the consequences and costs and dictate changes that can prevent further damage. It is the assumption in the present scenario that more of these initiatives are effectuated in Denmark in the future, and that there will be a direct influence on the amount of arable land, the yields and cost of agricultural production.
- The scenario includes an increase in the focus on perennial crops, increased biodiversity and more robust financial production through a broader selection of crops and increased priority on straw.

The European Environmental Agency (EEA) did an evaluation on sustainable biomass production in the EU in 2006. The evaluation included scenarios for 2030, and some of the guidelines from this work are included in the present scenario. These guidelines are listed below (EEA, 2006):

- Minimum 30 % of agricultural land is prioritized as “environmentally-oriented farming”.
- 3 % of the conventionally cultivated area is taken out of rotation as fallow fields compensation.
- The bio energy crops with the lowest environmental impacts are used.
- Current protected forest areas are maintained.

The choice of suitable energy crops to plant for energy production is based on an evaluation from the same work. The results of the evaluation are presented in Table 5-4 below.

Table 5-4: Evaluation of the environmental impact and suitability of several different crops for production of bio energy. A is low harmful impact on environment, B is medium and C is high (EEA, 2006).

	Permanent grass	Clover and alfalfa	Maize	Oilseed rape	Wheat	Sugar beet	Poplar and willow	Red canary grass
Erosion	A	A	C	B	A	C	A	A
Soil compaction	A	A/B	B	C	A	C	A	A
Nutrient inputs to ground and surface water	A	B	C	B/C	A	B/C	A	A/B
Pesticide pollution	A	A	C	C	B	B	A	A
Water abstraction	A	A	A/B	-	B	A/C	B	A/B
Increased fire risk	B	-	-	-	A	-	-	-
Link to farmland biodiversity	A	A/B	C	B/C	B/C	B	A/B	B
Diversity of crop types	A	A	B/C	A/B	C	B	A	A

Based on these considerations and assumptions, the set of parameters for the 2020 Eco scenario is:

- Total arable land area is reduced by 20,000 ha compared to 2008 reference due to new protection zones to mitigate the effect of pesticide use and nutrient leaching in fragile areas.
- Biomass yield from 30 % of total agricultural area is reduced by 15 % in output and 35 % in input due to increased focus on "environmentally-oriented farming". This corresponds to average yields of 95.5 % and average inputs of 89.5 % - except for forests, parks and gardens.
- Grass is harvested for maintenance of 75 % of protected areas (P-3 areas).
- 3 % of remaining area (ca 80,000 ha) is removed from production as fallow fields.
- Animal production is reduced by 50 %.
- Increased focus on biodiversity reduces the following areas: Winter wheat, spring wheat, spring barley and winter barley areas are reduced by 400000 ha, 200000 ha and 50000 ha, respectively.
- 150000 ha of additional spring wheat under sown with clover grass are added. It is assumed feasible to harvest approximately 2.5 t dry matter/ha clover grass.
- 50000 ha of additional spring triticale under sown with clover grass are added.
- 50000 ha of additional oat and 50000 of additional rye are added.
- 50000 ha of additional beets and root crops are added and 50000 ha of maize are added.

- 200000 ha of energy crops are added – including belts of willow that are planted between fields and natural water systems to absorb leached nutrients and pesticides.
- 50 % of all high fallow fields are used for energy crop production (willow or miscanthus grass).
- 75 % of all low areas not suitable for intensive agriculture is used for production of grass for biogas.
- Forest area and yields are similar to the other scenarios.
- 2.5 t dry matter/ha of clover grass is collected from under sown spring cereal fields.
- 50 % of clover grass, 75 % of manure, 50 % of straw from corn/maize, 50 % of root crop residues is collected for energy production.
- 85 % of cereal straw and 85 % of straw from seed production is collected from fields, and everything not used for animal production is used for energy purposes.
- Any parameter not defined specifically is assumed to be the same as for the previous scenario.

These settings give the following biomass dry matter yield in the model established in chapter 5.1:

Table 5-5: Energy potential of biomass produced and collected in a 2020 scenario integrating consideration on sustainability and environmental concern, and still aiming to fulfil the EU requirements of 30 % sustainable energy

	Output	**Output**	**Input**
	Megaton dry matter	PJ energy in available biomass (LHV)	PJ energy in diesel, natural gas etc.
Energy Crops	2.8	45.6	2.5
Straw from cereals	1.8	32.3	5.4
Straw from seed production	0.3	5.3	1.2
Wood and forest residues	1.7	33.1	1.2
Grass and clover grass	1.6	20.9	1.4
Corn/maize straw	0.2	4.2	0.3
Root crop residues	0.05	0.7	0.1
Manure	0.86	11.9	-
Total	9.4	154.0	12.0
Net output	-	142	

5.3.5 Biomass potential 2020 scenarios - summary

The previous three sections present three different scenarios for biomass potential evaluation in Denmark 2020. The differences in the scenarios' parameters seem more substantial than the variations in the results. Results from all three scenarios are summarized in Table 5-6 below:

Table 5-6: Summary of the results from three different 2020 biomass potential evaluations in Denmark

		Business-as-usual	**Climate change adaption and mitigation**	**Sustainability and environmental concern**
"Dry" biomass	LHV (PJ)	122.4	106.1	116.3
"Wet" biomass		24.4	47.0	37.7
Total biomass		146.8	153.1	154.0
Total input		12.4	14.5	12
EROI	-	11.8	10.6	12.8

The variation in total biomass energy yield in the three scenarios is only 7.2 PJ maximum. The difference in energy return on investment is more significant: 2.2 PJ/PJ, but the most significant difference is probably the difference in wet and dry biomass produced in the different scenarios. This difference will have a high impact on which technology is suitable for converting the biomass to consumable energy. None of the scenarios yield sufficient biomass to reach the EU goals of 30 % sustainable energy in 2020 – not without significant increases in average conversion efficiency. However, the Eco-scenario is quite close, lacking only around 3 PJ to meet the required 145 PJ.

When comparing the above results, it is important to remember that only some streams of crop waste/residuals are included. In many similar studies, municipal waste is included as a renewable biomass resource. This would add 25-35 PJ to the total potentials.

It is also important to regard the potential difference between the energy technology used at present, and the technology that will be used to convert the biomass in the future scenario. The political demand for 145 PJ of biomass has been defined under 2009 condition on a set of assumptions regarding the average conversion efficiency of the available technology and composition of conversion facilities in Denmark. Increasing the average conversion efficiency would decrease the demand accordingly. On the other hand, it is important to match the available biomass resource with the right conversion technology. Most types of biomass are more difficult to convert than wood – especially at a similar efficiency. This problem is discussed briefly in the next chapter.

This concludes the evaluation of the Danish biomass resource in three 2020 scenarios. The remaining task is to give an overall estimate on Danish bio-SNG potential by combining these findings with the data from the technology review and the methods described in the case studies.

6 Danish bio-SNG potential and use - calculations and conclusions

This chapter seeks to combine the findings of the report in a quantified assessment of the potential for bio-SNG production in Denmark and an overall look at the possibilities for using and producing bio-SNG in Denmark 2020 based on the findings in the report. The calculations of the potential will be based on the present day technology reviewed in the first part of the report and the methods already developed and used for other similar assessments in the case section. The most important data and results regarding the production technology and the biomass resource are collected in Table 6-1 and Table 6-2 below:

Table 6-1: Production technology overview for bio-SNG production in 2010

Gasifier		Milena	FICFB PDU	SilvaGas
Upgrade/cleaning		Cyclone, OLGA tar removal, zinc oxide beds, three-step TREMP® methanation system, Selexol™ scrubber and gas cooling	PSI/CTU isothermal fluidized bed methanation technology system and unknown system for removal of CO_2, H_2, NH_4 and water	Rentech Process Methanation on iron-based catalyst and gas upgrading technology by UOP LLC
Cold gas efficiency	%	80	65	36
Biomass-to-SNG efficiency	%	66	54	57
Overall process efficiency	%	82	97*	83

*incl. district heating

Table 6-2: Biomass resource potential as estimated for Denmark 2020 in three different scenarios

Scenario		Business-as-usual	Climate change adaption and mitigation	Sustainability and environmental concern
Woody biomass	LHV (PJ)	84	79	79
Herbaceous biomass		38	27	37
"Wet" biomass		24	47	38
Total biomass		147	153	154
Total input		12	15	12
Energy return (as LHV biomass) on energy investment ratio	-	12	11	13

6.1 Estimation of the Danish bio-SNG potential in 2020 scenarios

The approach used for the calculations in this report is almost similar to the approach used for estimation of the Canadian bio-SNG potential that was described in chapter 4.3.2. This implies that it is assumed that woody biomass and herbaceous biomass can be converted through gasification, gas cleaning and upgrading into bio-SNG. However, in opposition to the study from Canada, it is assumed that anaerobic digestion of the wet biomass with subsequent gas upgrading can contribute to the total bio-SNG potential.

In the study from Canada it is assumed that all biomass can be converted in the same process (Hacatoglu, et al., 2010). This is questionable as gasification of biomass normally focuses on woody biomass, since this is by far the most straightforward to convert. The low ash content in wood is essential for many gasification processes, and today there exist only a few processes, which are capable of converting more difficult types like straw or manure fibres. One of the very promising technologies is the LT-CFB (Low temperature circulating fluidized bed), which is capable of gasifying almost anything, but has some significant tar issues. In the overview on bio-SNG technology in section 3.1, only the SilvaGas gasifier with its low temperature and indirect gasification was capable of producing bio-SNG from other types of biomass than wood. Municipal waste, biomass, coal and PET-coke were mentioned for use in the SilvaGas gasifier. Combining and comparing the characteristics of the LT-CFB and the SilvaGas gasifiers it is assumed in the following that this technology has the best potential for converting herbaceous biomass in 2020. A Milena-like setup is used to convert the woody biomass.

It is not assumed feasible that any of the reviewed bio-SNG-technologies will be able to handle the extremely high ash content in manure fibres in any near future. Therefore, it is assumed in the calculation of the bio-SNG potential that the residual fraction from biogas production is returned to the fields instead of further processing. It is assumed that upgrading biogas to bio-SNG will require 4-7 % of the energy in the biogas (5.5 % is used in calculations) (Jensen, 2009). Data for biogas production capability on Danish manure and grass is from (Jørgensen, et al., 2008) and used for all wet biomass in the calculations. Combined with the biomass-to-SNG efficiencies this leads to the following estimations of the Danish bio-SNG potential in 2020:

Table 6-3: Estimation of the maximum potential for production of bio-SNG in Denmark in 2020 from domestic biomass resources

Scenario		Business-as-usual	Climate change adaption and mitigation	Sustainability and environmental concern
Bio-SNG from woody biomass	PJ	55	52	52
Bio-SNG from herbaceous biomass	PJ	22	15	21
Bio-SNG from "Wet" biomass and manure*	PJ	18	42	30
Total Bio-SNG potential in 2020	PJ	95	109	103
Total input	PJ	12	15	12
Energy return (in bio-SNG) on energy investment ratio	-	8	7	9

* Calculated as the fraction of pure methane from upgraded biogas subtracted the energy use in the upgrading process

According to the official Danish prognosis for energy consumption in the near future, the demand for natural gas is expected to be fairly stable towards 2020 resulting in a constant consumption rate of around

170 PJ of natural gas each year (Energistyrelsen, 2010). With the assumptions and limitations of the present work it is thus proposed that somewhere around 55-65 % of this quantity could be substituted by bio-SNG produced from the domestic biomass resource in 2020. This value is highly dependent on the development in agriculture, climate and bio-SNG production technology. Additional substitution could be applicable if production of bio-SNG from organic waste and the fibre residue from biogas production was included. This would probably add 20-30 PJ resulting in a total natural gas substitution of 65-80 %.

The estimation of the bio-SNG potential is based on a total use of the domestically available biomass and waste resource for bio-SNG production with technology that is barely mature at present. The feasibility and reasonability of the result is, therefore, open for discussion.

6.1.1 Process EROI and overall energy balance

As seen in Table 6-3, the Energy Return On energy Investment decreases from 11-13 units of biomass energy to 7-9 units of bio-SNG produced from every 1 unit of energy invested in the process. The $EROI_{SNG}$ of 7-9 corresponds well to the optimistic case in the Canadian study on bio-SNG. The Canadian base-case EROI was around 5-6, which is significantly lower than the results of the present work. To match the comparison between the two studies the net energy production in the present work is adjusted towards the settings in (Hacatoglu, et al., 2010) by the following:

- Transport of fresh biomass from production site to bio-SNG production facility is included as 15 km on average, transported on trucks with a fuel consumption of 0.18 litre diesel·km^{-1}·ton cargo^{-1} (Miljø&Energi_Ministeriet, 2001). This is also applied for the biogas process.
- 330 kWh electricity consumption per ton dry biomass converted to bio-SNG is included (Hacatoglu, et al., 2010). This corresponds to approximately 3 GJ of natural gas equivalent in a gas engine with 40 % electric efficiency. This is not applied for the biogas process.
- 2 GJ of electricity produced from the excess heat from the production of 20 GJ bio-SNG in a power generation cycle with a 30% electric efficiency is included in the balance. All remaining heat is assumed to cover the drying process of the fresh biomass (Hacatoglu, et al., 2010). The electricity is calculated to be the same as 2.6 GJ natural gas equivalent produced per ton dry biomass converted using the same gas engine as above. This is not applied for the biogas process.
- $EROI_{SNG}$ for gasification processes and anaerobic digestion processes are calculated separately.
- Wood is assumed to hold 45 wt% water, herbaceous biomass 25 wt% water, "wet" biomass 75 wt% water and manure 93 wt% water (Jørgensen, et al., 2008; Hacatoglu, et al., 2010).

These changes would decrease the $EROI_{SNG}$ in the three scenarios as indicated in Table 6-4 below:

Table 6-4: $EROI_{SNG}$ estimations for SNG produced in gasification process and in biogas process in three scenarios

Scenario	Business-as-usual	Climate change adaption and mitigation	Sustainability and environmental concern
$EROI_{SNG}$ Biogas	4.8	4.3	5.3
$EROI_{SNG}$ Gasification	5.6	5.8	5.8
Total scenario $EROI_{SNG}$	4.9	4.9	5.4

It would probably improve the EROI of the thermal gasification SNG process if the energy balance for the process was done with the possibility to produce district heating during the winter. However, the above calculations are made for the purpose of comparison with the study on Canadian SNG potential. In this respect, it is evident that the Canadian potential for energy efficient bio-SNG production is higher than the Danish ditto. Even with the inclusion of bio-SNG from upgraded biogas and the much larger distances in Canada, the Canadian EROI of the process is still significantly better (5-6 instead of 4-5). This could be based on differences in the calculations, but is also very likely to be influenced by the large wood resources from forest that exists in Canada. Wood from forests has a very low energy input compared to other types of biomass, and an increase in the Danish forest area would probably minimize the difference in process EROI of the two countries.

6.2 Use and production of bio-SNG in Denmark 2020

The proposal to substitute 55-80 % of the natural gas consumption with bio-SNG would require that the total domestic biomass resource is used for bio-SNG production, and the discussion on biomass use would thus change to a discussion on how we use natural gas/bio-SNG most optimally. It is hardly feasible for one conversion technology to be used on the entire biomass quantity, but for the purpose of discussion it is regarded as a possibility.

There are many excited discussions on the use of biomass for energy in Denmark in 2010, and there is no reason to expect less intensive discussions in the future. If an evaluation of the potential use of bio-SNG in Denmark should be included in these discussions, it would be reasonable to integrate some of the considerations from the report. From the case study it would be relevant to consider the following points:

- A case from Holland showed that the economic superiority of individual heat production from bio-SNG compared to CHP from biomass is highly dependent on two main factors. First of all, a large share of the used biomass has to be imported at port sites where SNG-facilities are situated to give the SNG-technology a benefit in transportation requirements. Secondly, the SNG-plant has to run for almost twice as many hours as the CHP plant. An argument for this could be that heat is mainly required in the winter period and SNG is storable. This argument, however, is not necessarily valid with new CHP plants, which are capable of operation in condensing mode. In this mode, the production of district heating would be traded for extra electrical efficiency.
- Using bio-SNG for heating would imply a conversion of low energy value biomass to high energy value SNG and then on to low energy value heat with intermediate pre-treatment, cleaning and upgrading operations. These operations reduce the overall process EROI significantly, and reduce the net output compared to direct heat production from e.g. gasification of the biomass.
- In two Swedish cases it was found economically feasible to co-produce district heating and bio-SNG for use as a high-value fuel for transportation. However, the cases from Sweden rely on a massive domestic wood resource and a relatively advanced fleet of gas driven buses for public transportation. Neither of the two prerequisites is present in Denmark, and, therefore, it is highly uncertain whether the conclusions from Sweden can be projected onto Danish conditions.
- Production of bio-SNG is more efficient in Canada, and other similar countries (like Sweden, Finland, Baltics etc.) due to a significant wood resource from large forest areas. Forests provide

highly suitable fuel for gasification purposes at much lower energy input rates than most other types of biomass. This results in a better process EROI and lower total energy consumption.

There are also some pointers to consider from the biomass evaluation section and the technology assessment. These pointers include the following:

- The future biomass resource will consist of many different types of biomass, and the variation will require high flexibility in the technology used for converting the biomass to energy.
- The present palette of technology for bio-SNG production from biomass focus on woody feedstock types, and is, therefore, more suitable for other countries than Denmark. A technology capable of converting different kinds of biomass with variations in ash content and moisture level would be required to fully utilize the potential in the Danish biomass resource.
- Wet biomass in the form of manure, ensiled grass, residues from fruits, beets etc. could be a significant contribution to biobased energy production in Denmark 2020. Biogas could, therefore, be a promising option for production of green methane. With the limitations and assumptions of the present study, upgrading biogas to bio-SNG seems to have a relatively good performance and a smaller energy requirement (better EROI) than bio-SNG production from gasification. Biogas production could be combined with gasification of the fibrous fraction of the degassed residue for CHP in LT-CFB like processes. This combined process could provide transportation fuel for buses and trucks, electricity, district heating and non-toxic, plant available ash mixed with the liquids from the biogas process for fertilizer.
- Most of the available gasification technology for production of bio-SNG has been adapted from alternative uses. To increase the profitability and feasibility of large-scale bio-SNG production from gasification of biomass, it seems likely that new and specialized gasification technologies would be highly competitive compared to the existing selection. Increased fuel flexibility, biomass-to-SNG efficiency and process EROI are essential if bio-SNG should succeed on a larger scale in a future Danish energy scenario.

These points lead to the following line of thought: With the present state of technology for bio-SNG production through gasification of biomass and the present state and direction of the Danish biomass sector and transportation sector bio-SNG is not the optimal choice for large-scale conversion of biomass to energy and other ways should be considered. Production of bio-SNG in Denmark lacks a unique selling proposition to make it favourable to other technologies. The main driver for introduction of bio-SNG in Denmark at present is to make use of the existing grid and equipment in the future. However, as there is assumed to be many years left with 100 % self-sufficiency of natural gas, it could be considered to use this phase as a step-by-step dismantling process instead of maintaining or expanding the grid to force a future bio-SNG production. As biomass is scarce in future energy scenarios, the technology for bio-SNG production would need improvements in the direction of e.g. higher overall energy efficiency, larger fuel flexibility, superior nutrient recycling and plant availability, superior economy etc. to be able to compete with alternative conversion technologies for the limited biomass resource. The prospects in bio-SNG are very interesting, but Denmark is at present not the optimal case for implementation. Introduction of gas driven public buses or trucks could probably change this. Significant increases in forest areas could change this. Improved bio-SNG production technology could change this.

6.3 Recommendations and future work

Bio-SNG from gasification has interesting perspectives and there are several different places in the energy sector where the technology could find justification in the future. However, neither technology nor society is at present ready for implementation, and the optimal use of bio-SNG produced from domestic biomass resources is yet to be displayed. As already mentioned, the existing gasification processes are not developed with SNG production in mind, and a fresh start might generate a more efficient gasification technology with better overall energy balance and EROI value. In this regard, it is also important to take into account that the available biomass in Denmark is not woodchips but a variety of herbaceous and moist feedstock. In the present report it was assumed that bio-SNG could be produced from herbaceous biomass in 2020, but this is a severe assumption, which is essential to verify as there is no such technology available at the present with satisfactory characteristics and efficiency. With a gasifier developed specifically for SNG production from a variety of biomass the overall EROI of bio-SNG production could improve significantly. The present work gives an overall evaluation of the potential for biomass in Denmark; it does not give a detailed analysis of the usability of the biomass for SNG production. However, the findings show that there is a potential for SNG production from thermal gasification of biomass. In order to give a more precise value for the potential a more thorough study would be needed.

The recommendations, based on this work, are that a more thorough analysis of the overall process - including thermodynamic studies and detailed chemical analysis, should be made so that a more SNG-minded gasification concept could be proposed. To use these studies for evaluations of bio-SNG potential, it would be beneficial also to refine and upgrade the biomass potential model so that the biomass potential for gasification could be estimated more precisely, and technology and availability of different biomass types could be matched more thoroughly.

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8 Appendix

Appendix 1: Parameters for biomass potential evaluation

Parameter	Unit	Value	Reference
Denmark total area 2007	Mio. ha	4,3	Statistikbanken.dk
Agriculture area 2007	Mio. ha	2,7	
Cereal crop areas 2007	Ha	1445158	Statistikbanken.dk and (Blume, et al., 2008)
Spring barley	Ha	457408	
Winter barley	Ha	168824	
Spring wheat	Ha	7906	
Winter wheat	Ha	683764	
Oat	Ha	55563	
Rye	Ha	30047	
Triticale and others	Ha	41646	
Seed production areas 2007	Ha	267276	
Spring rape	Ha	1030	
Winter rape	Ha	178812	
Seeds for sowing	Ha	87262	
Other seeds for industrial purposes	Ha	172	
leguminous plant areas 2007	Ha	5639	
Peas and others	Ha	5639	
Beets and root plants	Ha	84344	
Potatoes	Ha	41224	
Sugar beets and fodder beets	Ha	43120	
Permanent grass areas 2007	Ha	471359	
Grass and clover in rotation	Ha	262429	
Maize	Ha	144869	
Grain and legumes for silage	Ha	60379	
Lucerne	Ha	3682	
Protected P-3 areas 2007	Ha	340157	
Fallow fields 2007	Ha	221312	
P-3 areas 2007			
Salt meadow	Ha	34646	(Buttenschøn, 2007)
Marsh and fen	Ha	91339	
Insipid meadows	Ha	102362	
Heath	Ha	83465	
Common	Ha	28346	
Areas requiring management	Ha	300000	
Areas in MVJ	Ha	100000	
Late hay harvest (management)	Ha	100000	
Fallow fields 2007			
Energy forest and grass	Ha	3247	(Jørgensen, et al., 2008)
Grass and plant cover on low lands	Ha	103965	
Grass and plant cover on high lands	Ha	110600	(Jørgensen, et al., 2008)
Other fallow areas	Ha	3500	
Large forest areas 2007			
Broad-leaved trees	Ha	190440	Statistikbanken.dk
Pine trees		317400	
Assisting areas	Ha	15870	
Temporarily without growth	Ha	5290	
Small forests, parks and gardens 2007	PJ	10	(Klima-&Energiministeriet, 2010)

	Primary crop			Crop residue					Average	
	Fresh weight	Dry matter	Water content	Fresh content	Dry matter	Water content	LHV	Ash content	Production input	
Crops	**t/ha**	**t/ha**	**wt%**	**t/ha**	**t/ha**	**wt%**	**MJ/kg**	**wt%**	**GJ/ha**	
Conventionelle crops										
Spring barley	4,55	3,87	15	2,5	2,3	7	17,8	4	13,7	
Winter barley	5,65	4,8	15	3,11	2,9	7	17,8	4	17,1	
Spring wheat	3,62	3,08	15	1,82	1,7	9,3	17,8	4,9	13,9	
Winter wheat	7,04	5,98	15	3,87	3,5	9,3	17,8	4,9	18,5	
Oat	3,95	3,36	15	2,37	2,1	13	17,9	7	12,6	
Rye	4,73	4,02	15	3,79	3,6	6,1	18	3,3	15,5	
Titicale + etc.	4,93	4,19	15	3,94	3,4	13	17,8	3,5	16,2	
Spring rape	1,87	1,65	12	1,68	1,6	6,6	17,9	4,8	13,8	
Winter rape	3,49	3,07	12	3,1	2,9	6,6	17,9	4,8	17,4	
Peas + etc.	3,1	2,67	14	1,57	1,4	14	-	-	7,0	
Portatoes	39,7	9,92	75	0	0,0	-	-	-	20,5	
Sugar beets and fodder beets	55,9	12,3	78	7,2	1,6	78	11,8	-	18,3	
Clover grass	42,9	8	81	-	-	-	11,8		5,7	
Maize	11	9,35	15	3,5	3,2	8	19	2	18,8	
Lucerne	50,7	14	72	-	-	-	16,8	-	3,7	
Grass on P-3 areas	-	2,0	-	-	-	-	16	-	1,4	***
Grass on fallow fields	-	3,5	-	-	-	-	16	-	1,4	***
Energy crops on farm soil										
Willow	18	12	50	-	-	-	16,1	2,2	10,0	
Miscanthus	9,9	9	10	-	-	-	17	3,8	9,0	
Hemp	13,5	12,0	12,5	-	-	-	16,2	9	10,4	*
Energy crops on marginal soils										
Willow	15	10	50	-	-	-	16,1	2,2	10,0	
Miscanthus	8,25	7,5	10	-	-	-	17	3,8	9,0	
Hemp	11,3	10,0	12,5	-	-	-	16,2	9	10,4	*
Wood for energy purposes										
Broad leafed trees	1,7	1,18	45	-	-	-	19	0,6	1,4	***
Pine trees	2,9	1,85	55	-	-	-	19	0,6	1,4	***
Small trees - park, forest, garden**	2,3	1,52	50	-	-	-	19	0,6	1,4	**
Wood - total yield from extra forest areas compared to 2007										
Broad leafed trees		2,90								
Pine trees		4,54								

References follow the color codes on the next page

Bjerg (2001)

(Fødevareministeriet, 2008)

(Blume, et al., 2008)	AgroTech (2008)
(Jørgensen, et al., 2008)	Landbrugsinfo.dk
(Force_Technology, 2010)	Statistikbanken.dk / vb108 (1996)
(Force_Technology, 2010) unknown straw	As clover grass
(Boateng, et al., 2006)	Assumed to be 5/6 the yield from farm fields

*** Assumed the same as the diesel use of grass production

** Assumed to have average values of brad leafed trees and pine trees

* Calculated from Blume (2008) and landbrugsinfo.dk

Straw yield and use - average values from 2006-08

	Straw total	**For energy**		**For animals**		**Not collected**	
	mio kg.	mio kg.	% of total	mio kg.	% of total	mio kg.	% of total
Winter wheat	2609	994	38	626	24	989	38
Spring wheat	19	5	28	5	25	9	48
Rye	111	42	38	34	30	35	32
Triticale	131	36	27	44	33	52	40
Winter barlet	459	107	23	233	51	119	26
Spring barley	1332	250	19	774	58	307	23
Oat and mixed cereals	182	21	11	50	27	111	61
Winter rape	493	74	15	21	4	399	81
Spring rape	3	0	9	0	3	2	88
Legumes	11	0	3	1	5	10	92
Total	**5348**	**1529**	**29**	**1786**	**33**	**2033**	**38**

Statistikbanken.dk

Farm animals 2008		
Horses	60029	units
Total livestock	1564393	Units
Total pigs	12737648	Units
Total sheep	136049	Units
Total Pig Equivalents	14498119	Units
Straw use per PE per year	**123**	**Kg per PE**

Statistikbanken.dk

Manure production			
Manure per PE	2,5	ton/year	mst.dk
Dry matter content	6,4	%	Jørgensen (2004)
CH4 pr ton dm	289,1	m3 CH4/ton dm	Jørgensen (2008)
Energy content	0,036	PJ/mio m3 CH4	Jørgensen (2008)
Energy production	9,8	MJ/kg dm	Jørgensen (2004)

mst.dk

Straw use per PE per year	**133**	**Kg per PE**

Jørgensen (2008)

Biogas from permanent grasses		
CH4 per ton grass dm	350,0	m3 CH4/ton dm

Jørgensen (2008)

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